Dominios magnéticos: conceptos básicos y técnicas de observación

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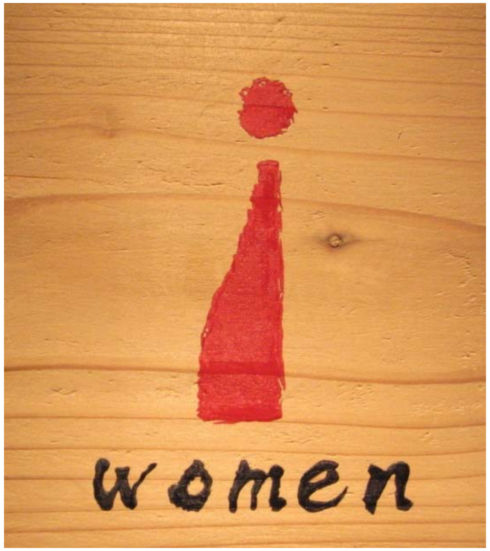
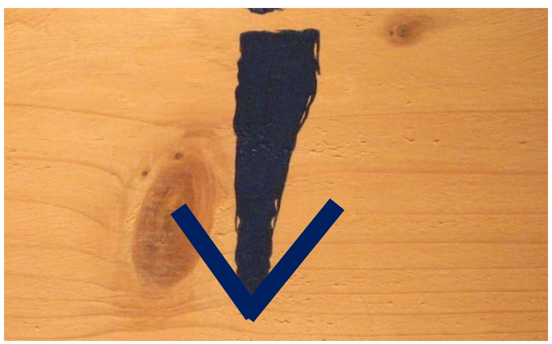
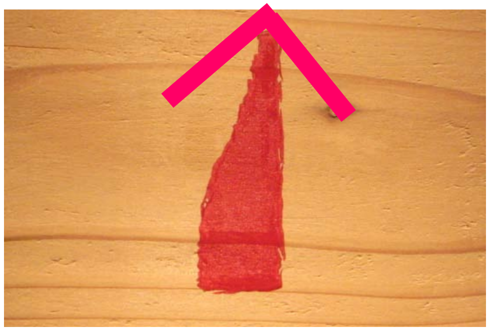
http://www.imm.cnm.csic.es/magnetoplasmonics

Un poco de diseño japonés (Otari)…







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Conceptos básicos:

- Un poco de historia
- Energías responsables.
- Paredes de dominio, dominios de cierre.
- Transición monodominio-multidominio

Técnicas de observación:

- Bitter
- Microscopía magneto-óptica
- Microscopías electrónicas
    1. Lorentz
    2. SEMPA
- Microscopías de barrido
    1. de fuerzas magnéticas (MFM)
    2. de efecto túnel polarizado en espín (SP-STM)
    3. de electrones balísticos (BEMM)
- Con radiación sincrotrón: X-PEEM

Comparativa entre diversas técnicas

Un poco de historia

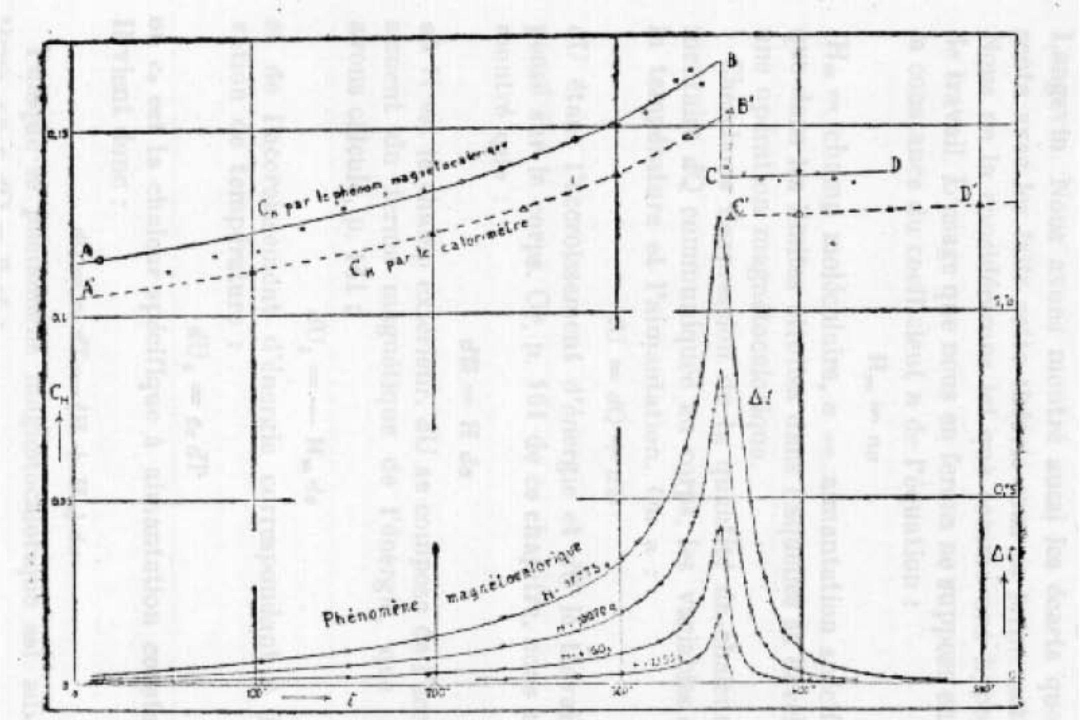


FIG. 51. — CHALEURS SPÉCIFIQUES ET PHÉNOMÈNE MAGNÉTOCALORIQUE, en fonction de la température.

Anomalía en el calor específico

P. Weiss et G. Foëx, *Le magnétisme*, (Colin 1926 et 1951)

Existe una imanación local M (T)…

(cortesía de André Thiaville, CNRS)

Un poco de historia

Imanación M → Campo molecular n M

En presencia de un campo H:

$$E_{mag} = -\frac{1}{2}\mu_0 n M^2 - \mu_0 M H$$

$$C^p \Delta T = \frac{\partial E}{\partial T} = -\mu_0 (nM + H) \frac{\partial M}{\partial T}$$

$$M(T) = M_0 \sqrt{1 - T / T_c} \Rightarrow \frac{dM}{dT} = -\frac{M_0}{T_c} \frac{1}{\sqrt{1 - T / T_c}}$$

(cortesía de André Thiaville, CNRS)

Un poco de historia

…Pero no hay
imanación M
sin aplicar un campo H

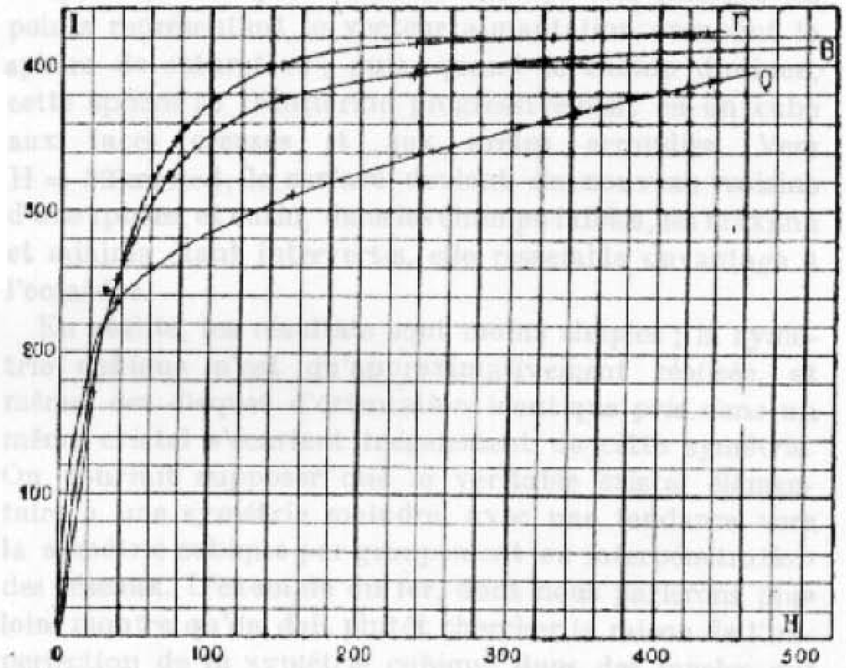
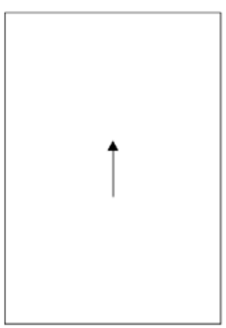


FIG. 37. — AIMANTATION DU CRISTAL DE MAGNÉTITE, suivant les axes ternaire, binaire et quaternaire.

P. Weiss et G. Foëx,
Le magnétisme,
(Colin 1926 et 1951)

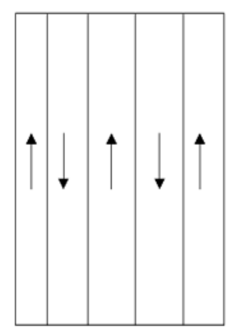
Hipótesis de la existencia de dominios magnéticos:
P. Weiss, J.Phys., 6(1907)401



$\langle M^2\rangle = 1$

$\langle M_x\rangle = 0$

$\langle M_y\rangle = 1$



$\langle M^2\rangle = 1$

$\langle M_x\rangle \approx 0$

$\langle M_y\rangle \approx 0$

Un poco de historia

…Pero no hay
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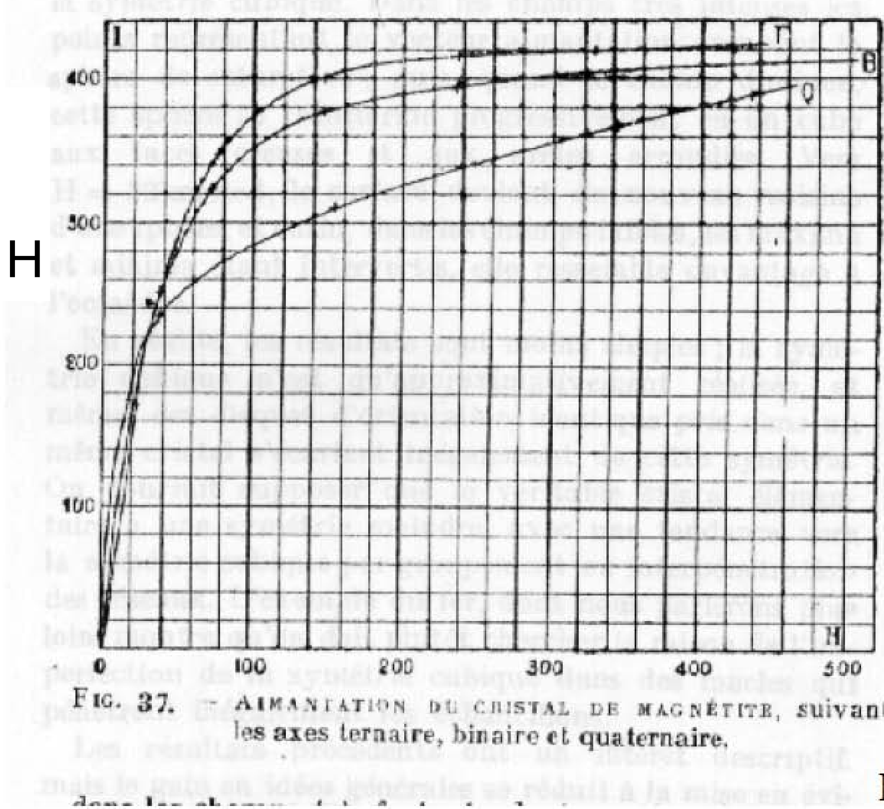
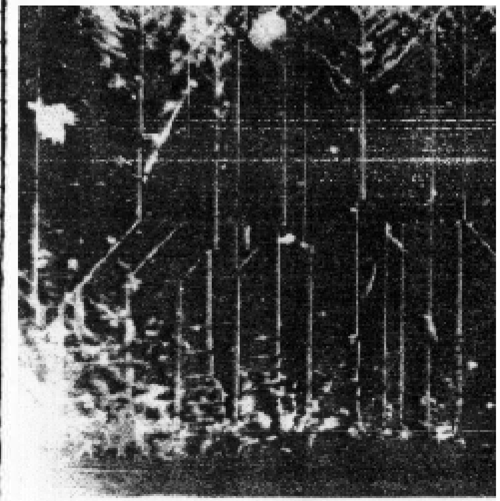
sin aplicar un campo H





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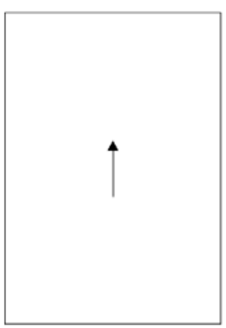
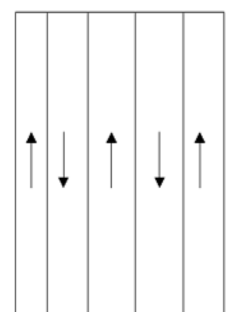


$$<M^2> = 1$$
$$<M_x> = 0$$
$$<M_y> = 1$$



$$<M^2> = 1$$
$$<M_x> \approx 0$$
$$<M_y> \approx 0$$

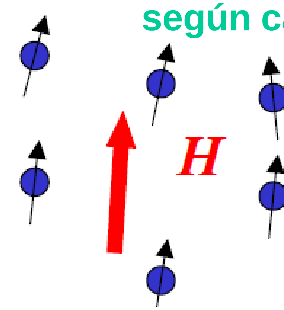
Energías responsables

$$\vec{M} = M_s(T)\vec{m} \qquad \left|\vec{m}\right| = 1$$

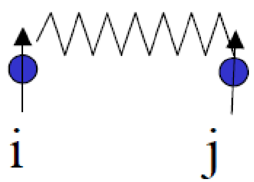
$$E = A(\vec{\nabla}\vec{m})^2 + KG(\vec{m}) - \mu_0 M_s \vec{m}\cdot\vec{H} - \frac{1}{2}\mu_0 M_s \vec{m}\cdot\vec{H_D}$$

canje magnetocrist. Zeeman magnetostática

Zeeman: quiere espines según campo aplicado



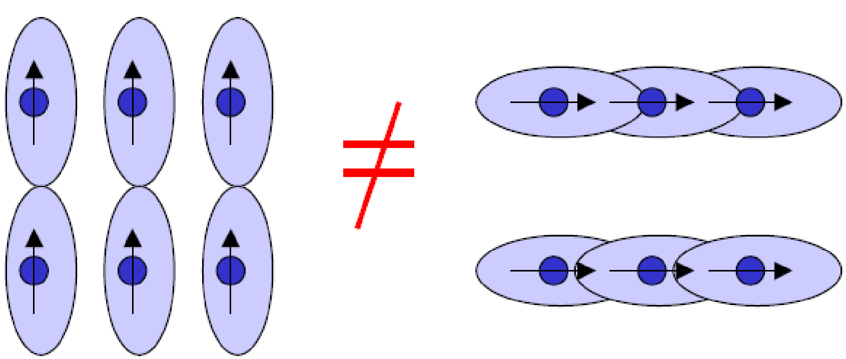
Canje: quiere espines paralelos

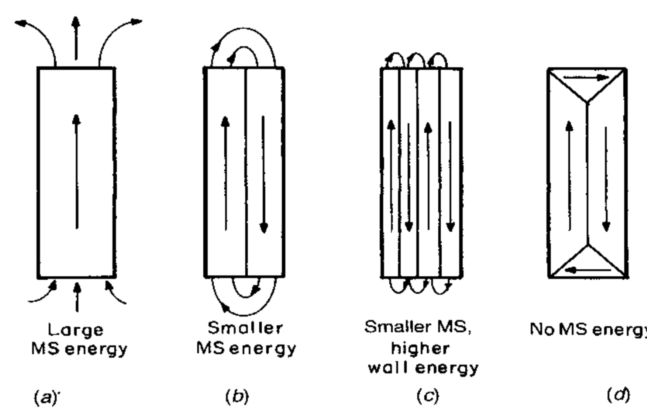


$$E = -J\vec{S_i}\cdot\vec{S_j}$$

Magnetostática: quiere cierre de flujo o muchos polos

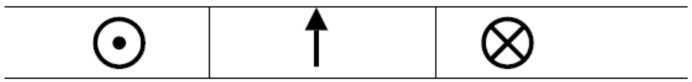
Magnetocrist.: quiere espines según ejes fáciles



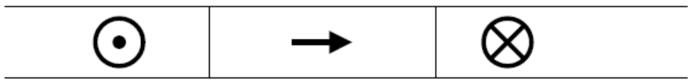


Paredes de dominio

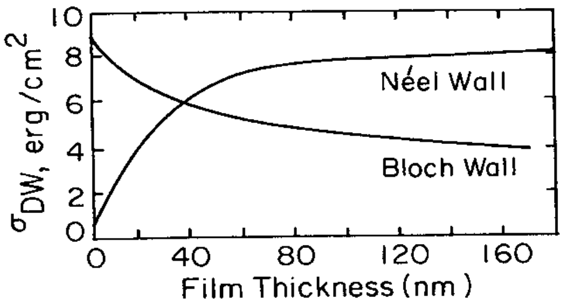
Paredes de dominio



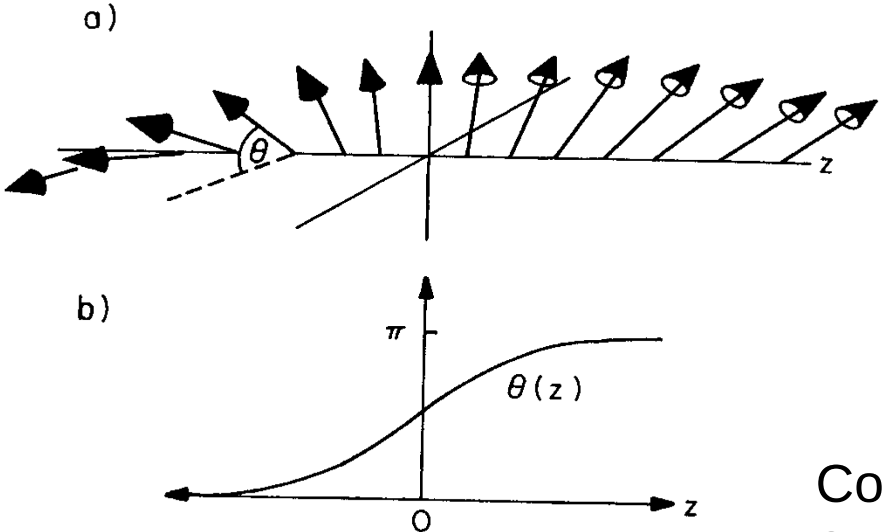
Pared de Bloch (1932)



Pared de Néel (1955)



Ejemplo: paredes de Bloch



Energía de pared

$$\sigma_{dw} \approx 2\pi(AK_u)^{1/2}$$

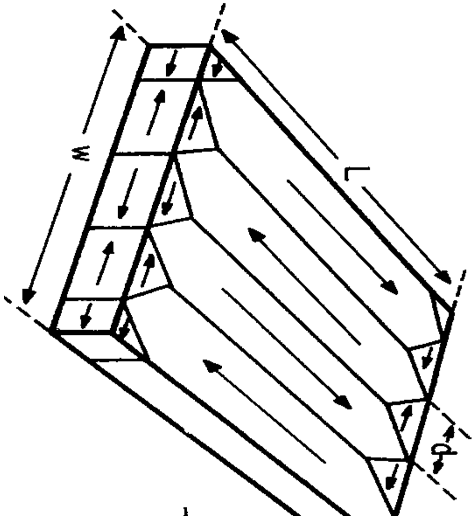
Anchura de pared

$$\delta \approx \pi(A/K_u)^{1/2}$$

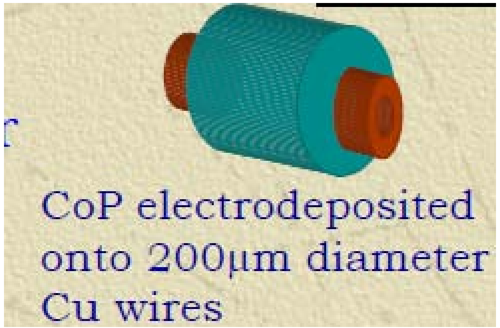
Como A~10^{-11} J/m y K~10^{2}-10^{6} J/m^3:

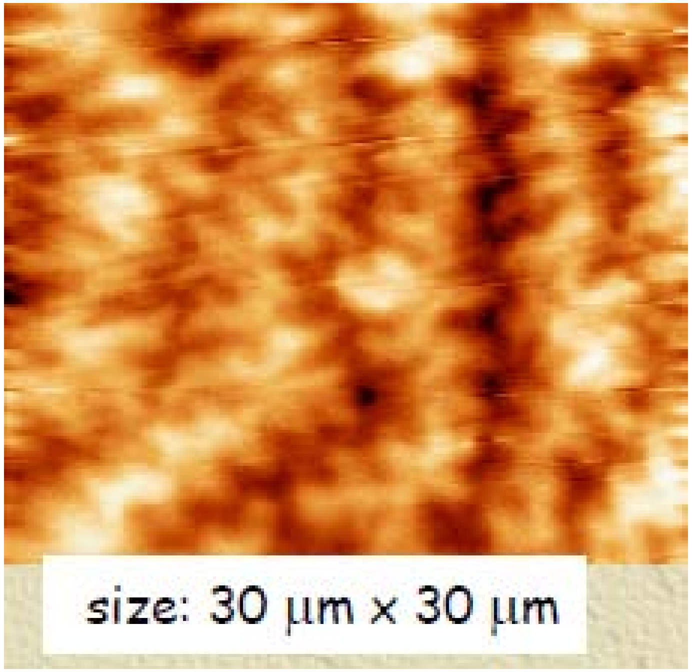
δ de unos pocos a unos cientos de nm

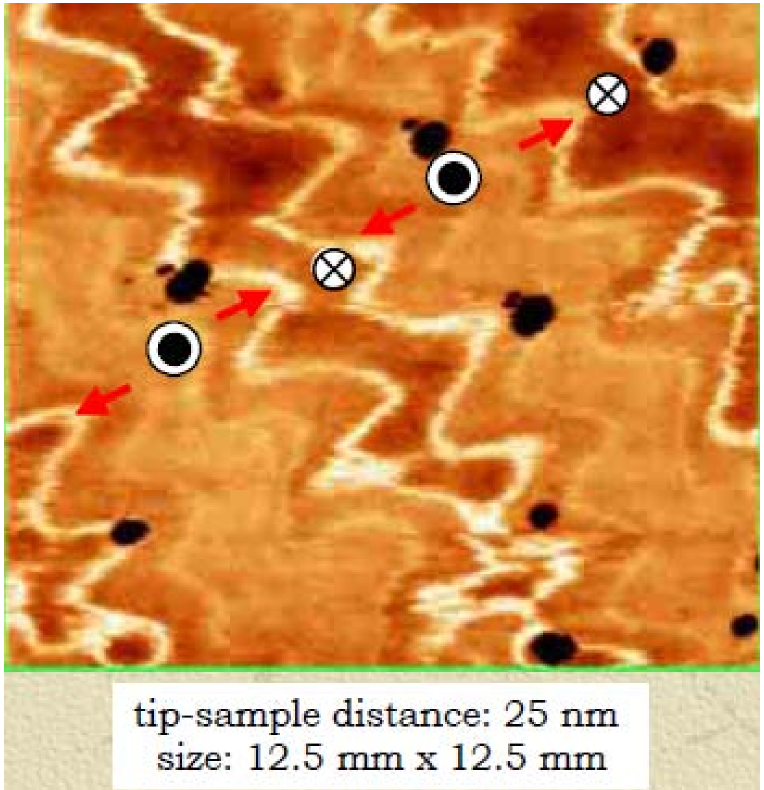
Dominios de cierre



La anisotropía es inferior
al campo desimanador





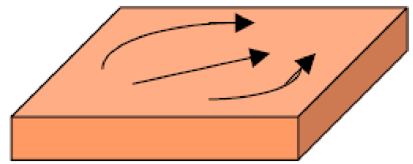


Transición monodominio-multidominio

R.P. Cowburn et al. APL **72** 2041 (1998)

permalloy

$\Lambda = 5$ nm



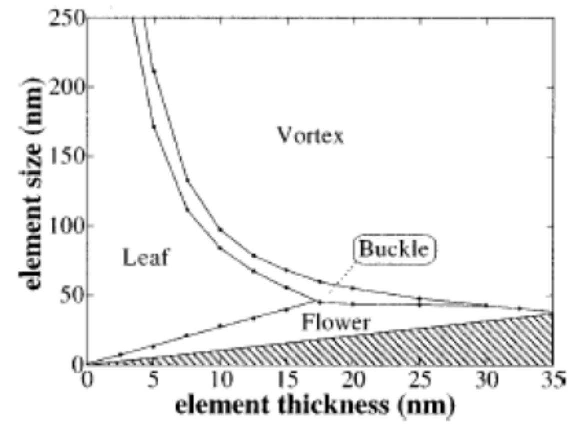
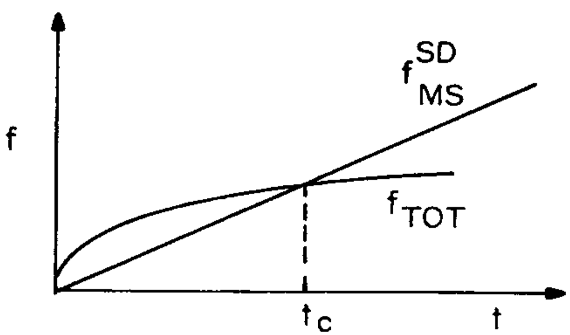
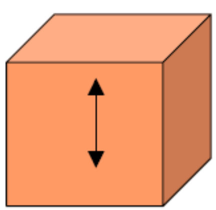


FIG. 3. The magnetic phase diagram of square planar nanostructures. The diagram gives the (global) lowest energy magnetization configuration as a function of the magnetic element size and thickness. The shaded region represents columnar elements which have not been addressed in this work.

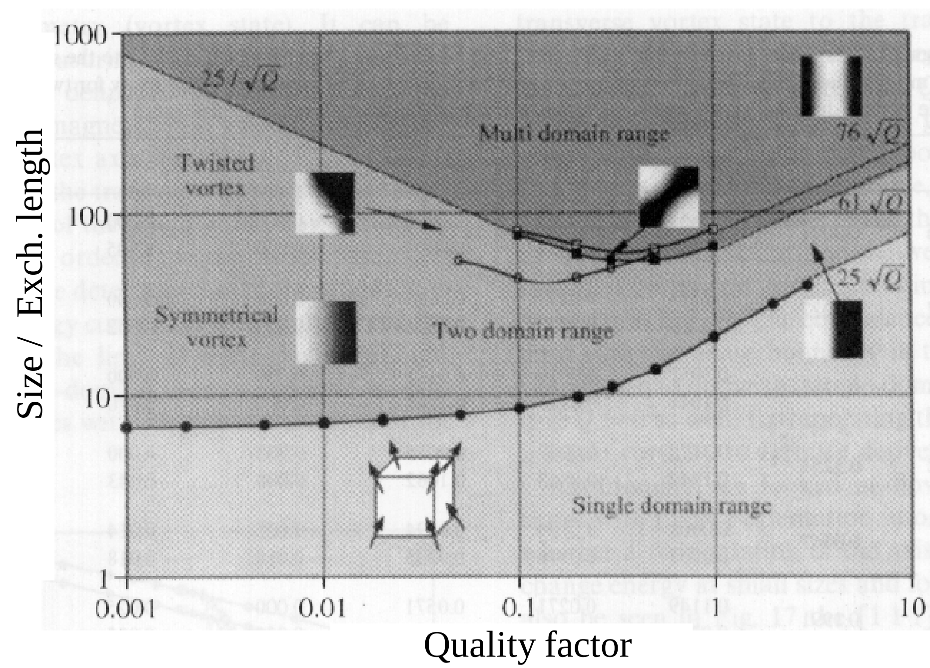


Llegado un cierto tamaño, la Emagnetos. del monodominio es demasiado grande



Quality factor

$$Q = \frac{2K}{\mu_0 M_s^2}$$

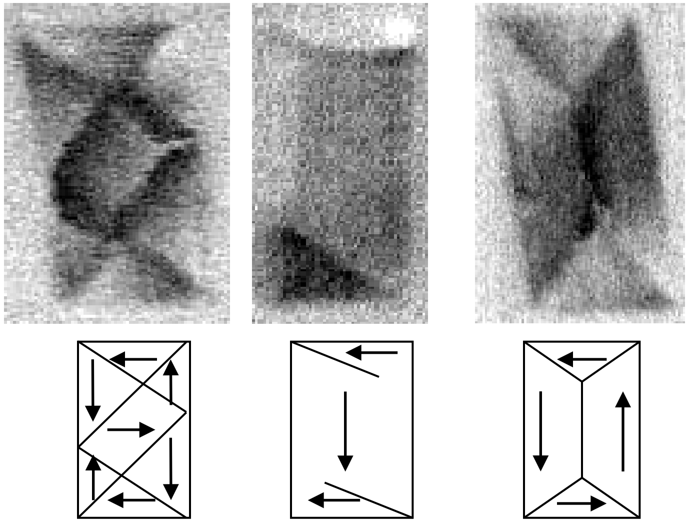


W. Rave et al. JMMM **190** 332 (1998)

Transición monodominio-multidominio

La estructura de dominios depende de la historia magnética

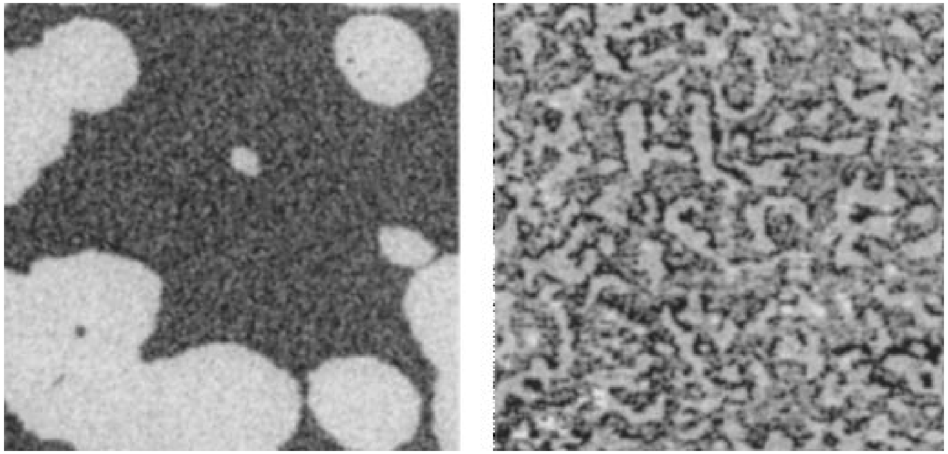
Permalloy elements
1x2 microns



After perpendicular H

After in-plane H

Au / Co 1nm / Au



Size: 1mm

Size: 20 microns

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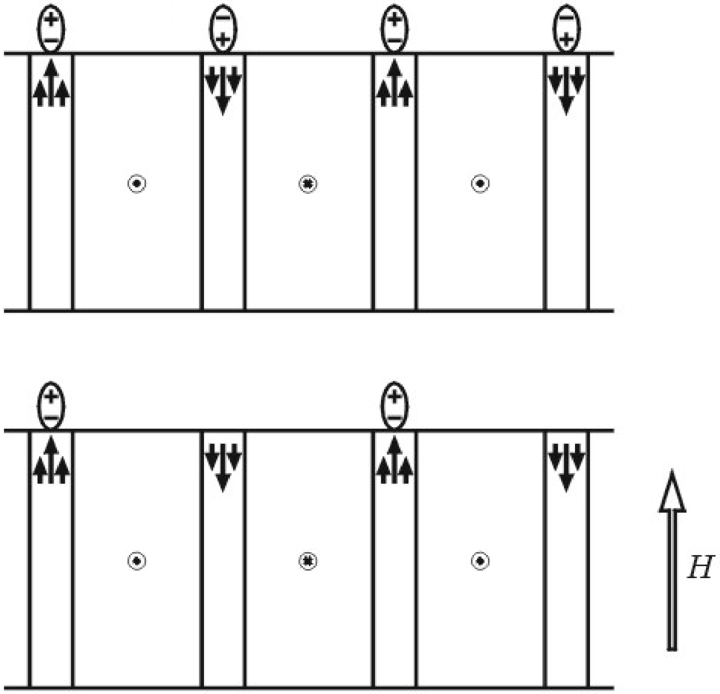
- Con radiación sincrotrón: X-PEEM

Comparativa entre diversas técnicas

Técnica Bitter

- Partículas magnéticas en suspensión coloidal sobre una superficie: se colocan donde hay gradiente de campo
- Se observan por microscopía óptica

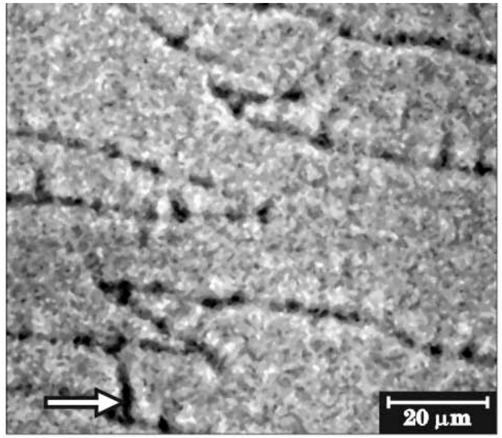


Técnica Bitter

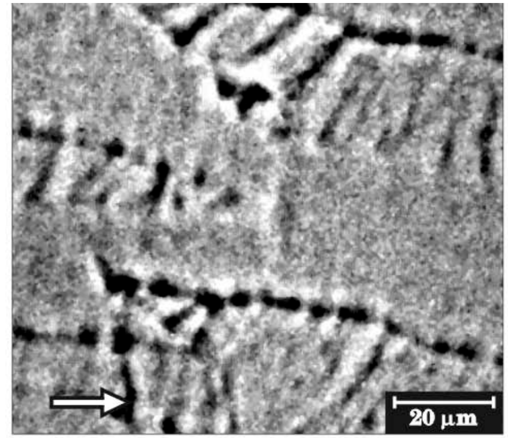
In-plane anisotropy

100 nm Co film
evaporated at 45º incidence
(arrow: atom flux projection)

H=0



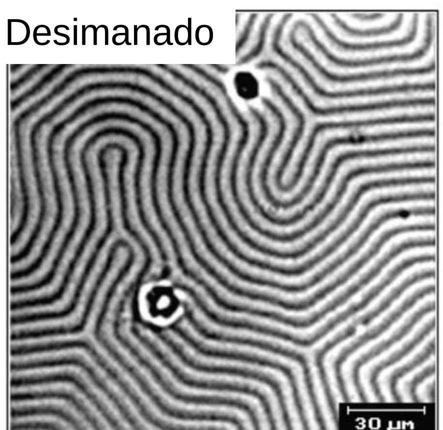
Hperp=300 Oe



Perpendicular anisotropy

$Y_{2.6}Sm_{0.4}Fe_{3.8}Ga_{1.2}O_{12}$ garnet

Desimanado

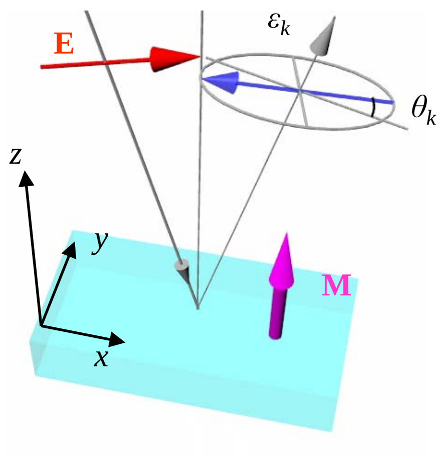


Saturado

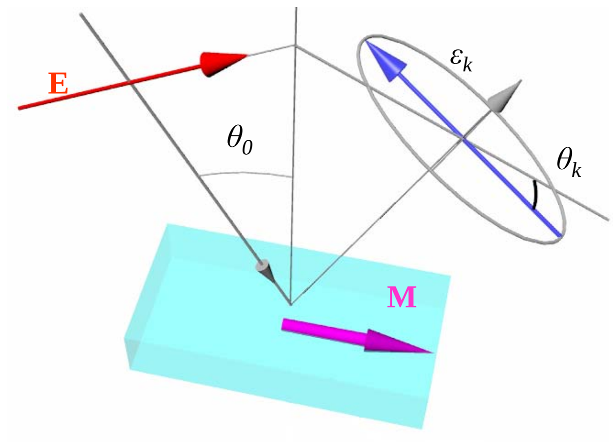
W. Szmaja, in: Advances in Imaging and Electron Physics, Ed. P.W. Hawkes, Vol. 141 (2006) pp. 175-256
J. Magn. Magn. Mater. 234 (2001) 13-18

Efecto Kerr Magneto-óptico

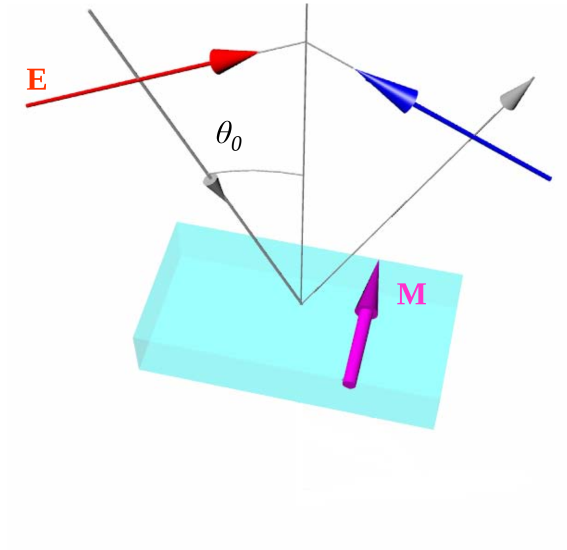
Polar

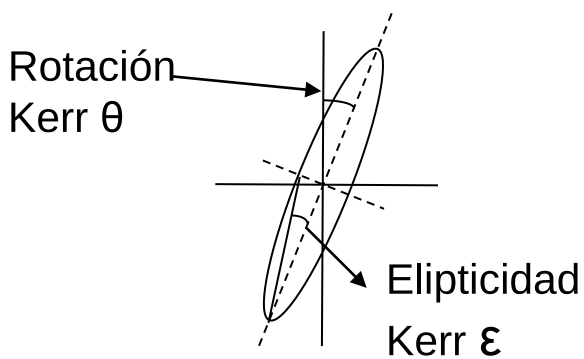


Longitudinal



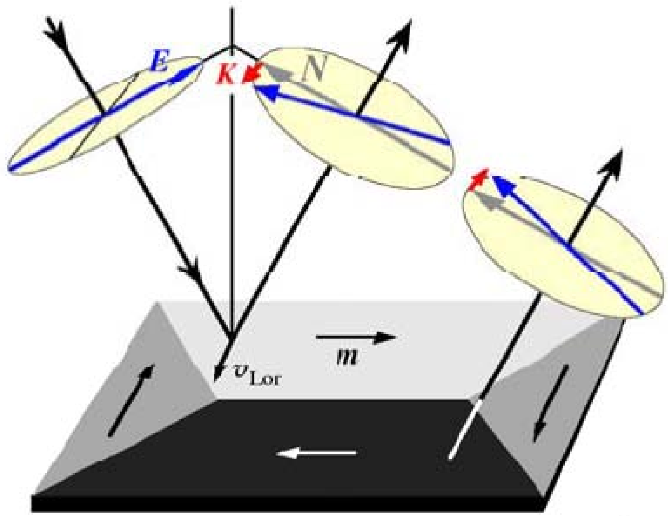
Transversal

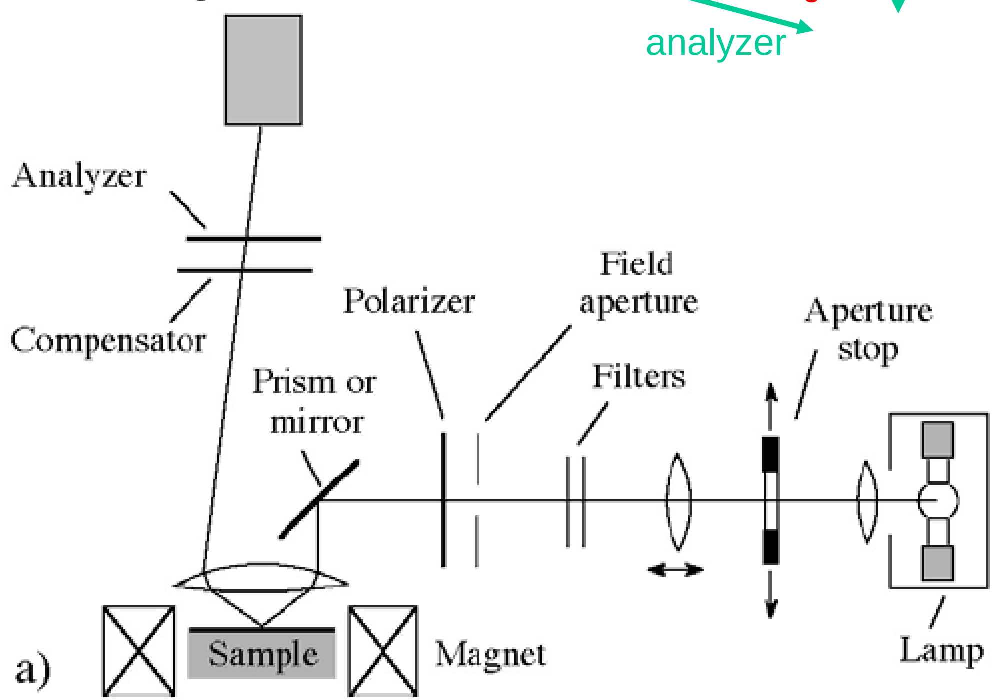


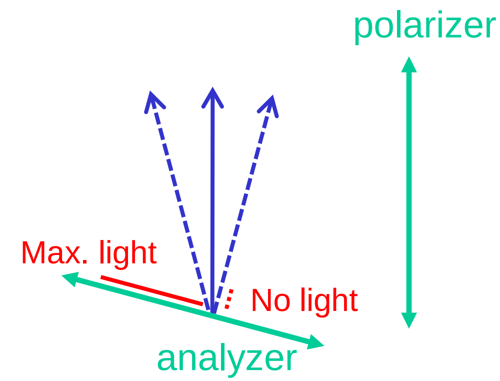


ΔR

Kerr Microscopy



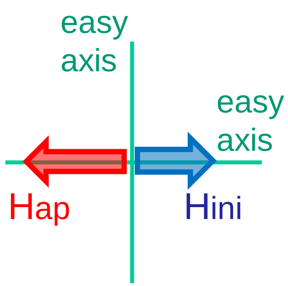


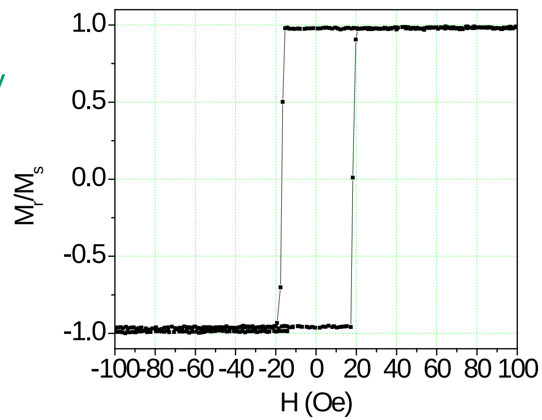


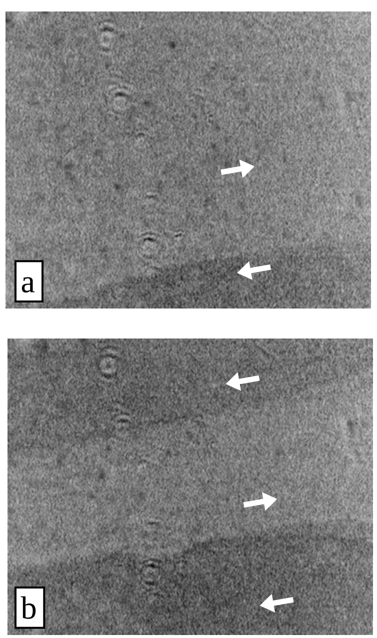
Kerr Microscopy

epitaxial γ'-Fe_4N

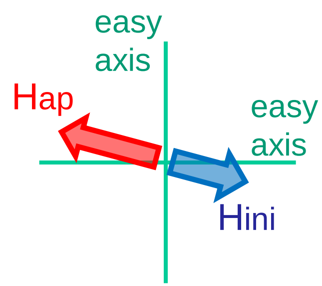
0º

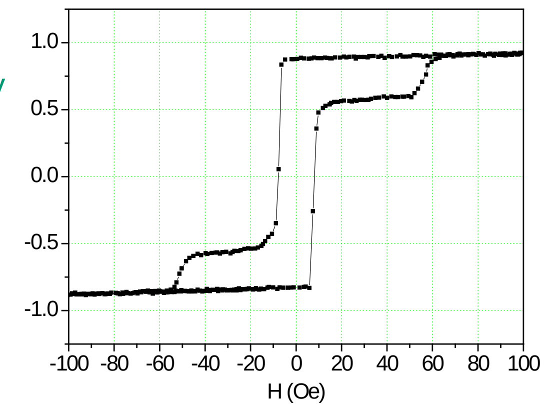


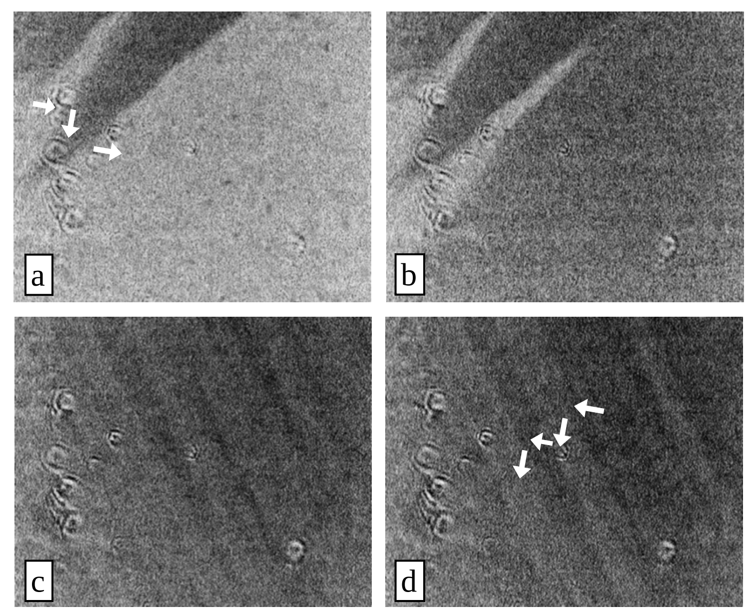




15º



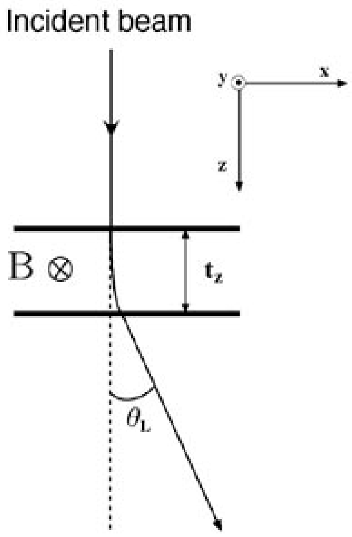




Lorentz Transmission Electron Microscopy

La Fuerza de Lorentz

$$\mathbf{F} = -|e|(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$



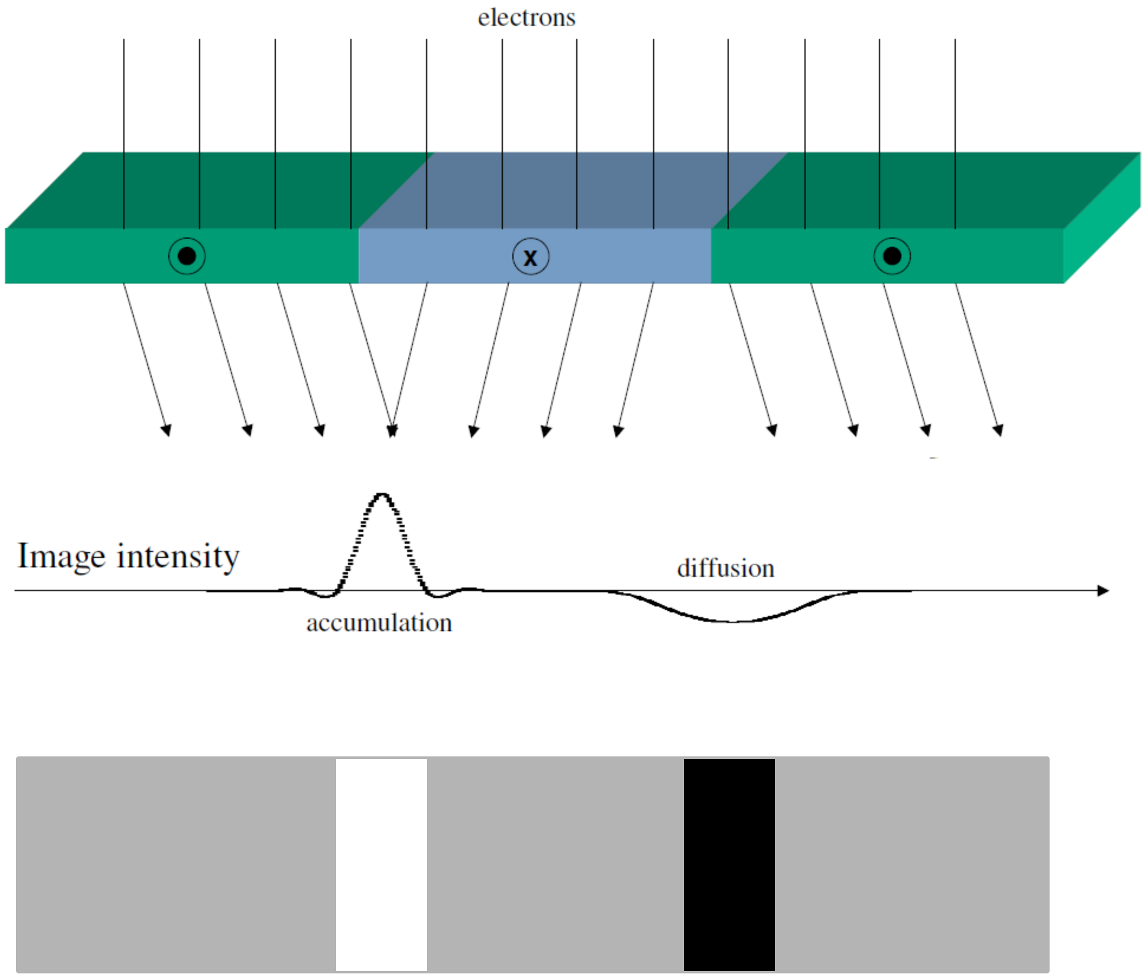
Se basa en introducir una aberración controlada en la función de transferencia de un TEM. La aberración puede ser:

•el desenfoque (modo Fresnel)

•una apertura en el plano de difracción (modo Foucault)

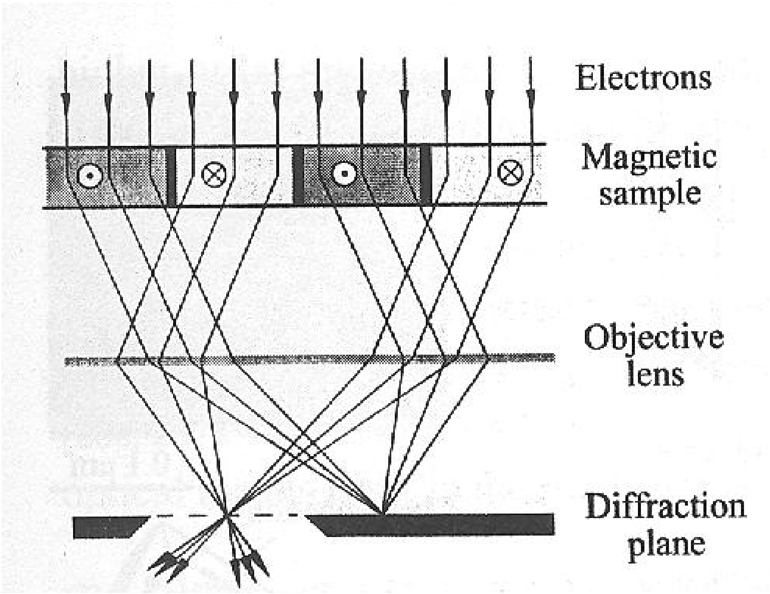
Lorentz Transmission Electron Microscopy

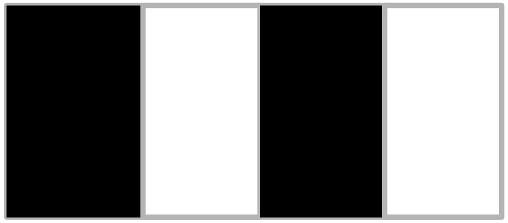
Fresnel mode



Lorentz Transmission Electron Microscopy

Foucault mode

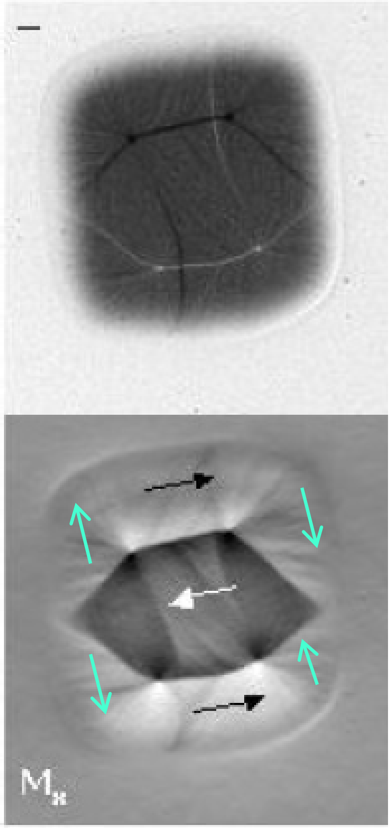




Lorentz Transmission Electron Microscopy

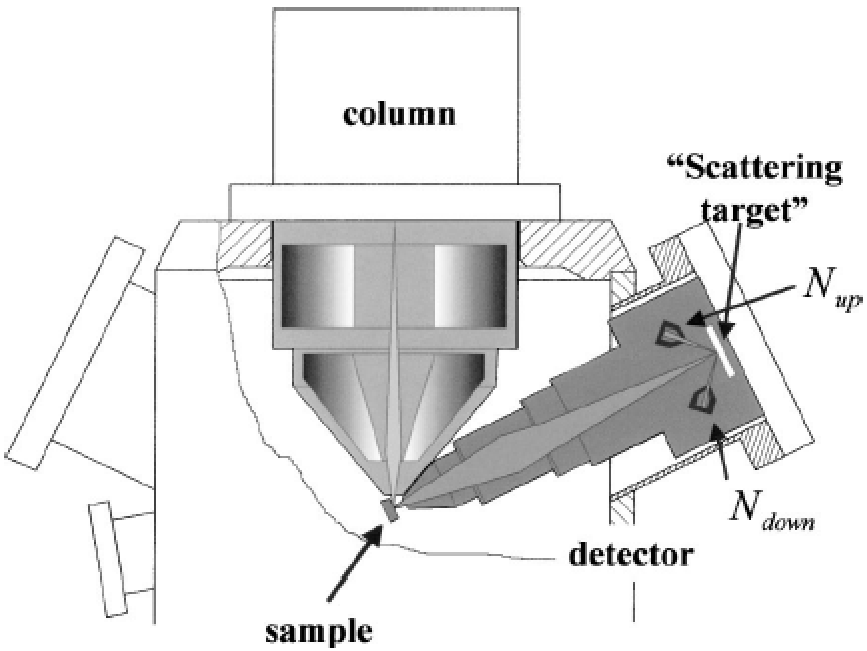
En el modo Fresnel vemos Paredes

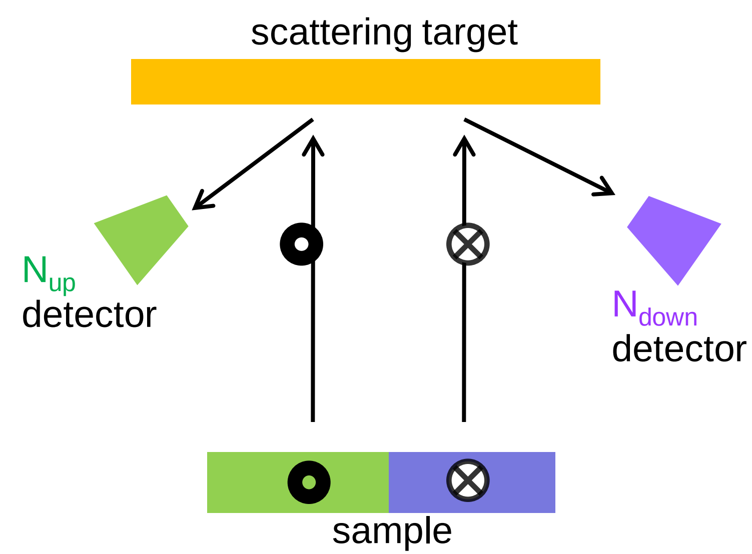
En el modo Foucault vemos Dominios



Polycrystalline Co nanostructure

Scanning electron microscopy with polarization analysis (SEMPA)

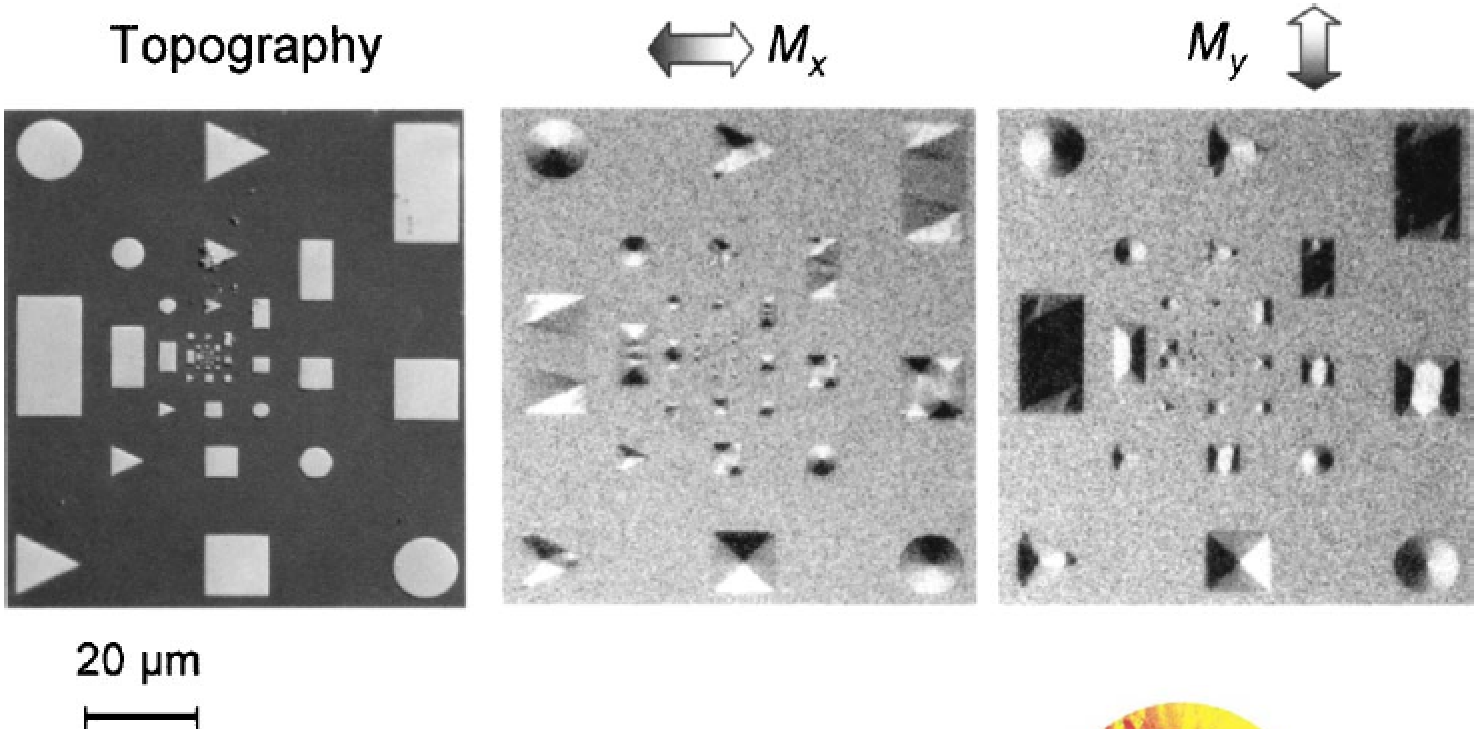




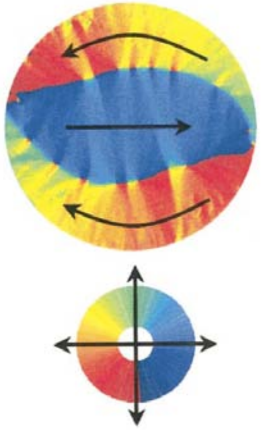
Signal=(N_{up}-N_{down})/(N_{up}+N_{down})

- Contrast due to the spin polarization of secondary electrons emitted from a magnetic sample
- The "scattering target" is a gold thin film (large spin orbit)
- Only suitable for surface analysis (1 nm)

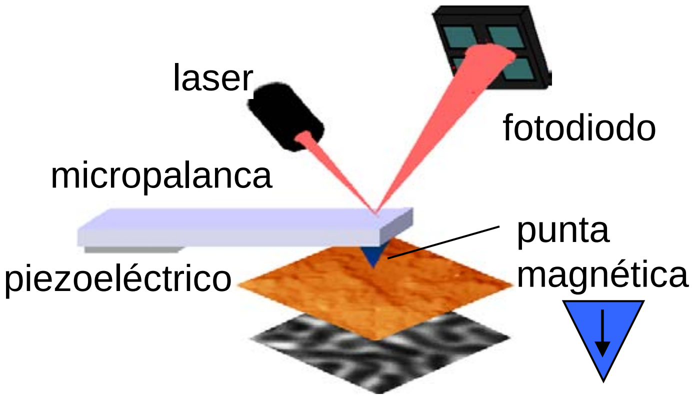
Scanning electron microscopy with polarization analysis (SEMPA)

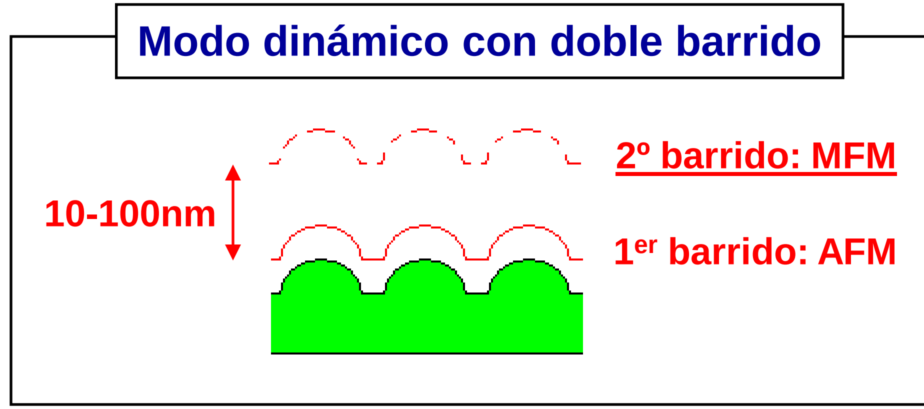


from Oepen et al., J. Vac. Sci. Techno. B **20**, 2535 (2002)



Magnetic Force Microscopy (MFM)

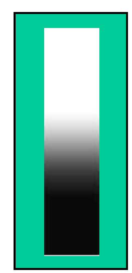




$$\frac{d^2z}{dt^2} + \frac{\omega_0}{Q}\frac{dz}{dt} + \omega_0^2\, z = \frac{F_{vib}}{m}\cos(\omega_{vib}\, t) + \frac{F_z^{ext}}{m}$$

$$\frac{d^2z}{dt^2} + \frac{\omega_0}{Q}\frac{dz}{dt} + \omega^2\, z = \frac{F_{vib}}{m}\cos(\omega_{vib}\, t)$$

$$\boxed{d\omega = \omega - \omega_0 \approx -\frac{\omega_0}{2k}\frac{\partial F_z^{ext}}{\partial z}}$$



$d\omega > 0 \rightarrow$ repulsión

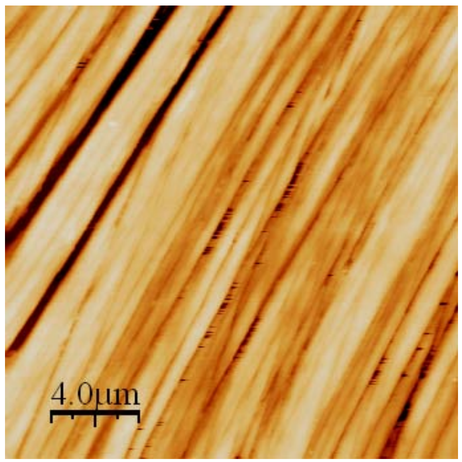
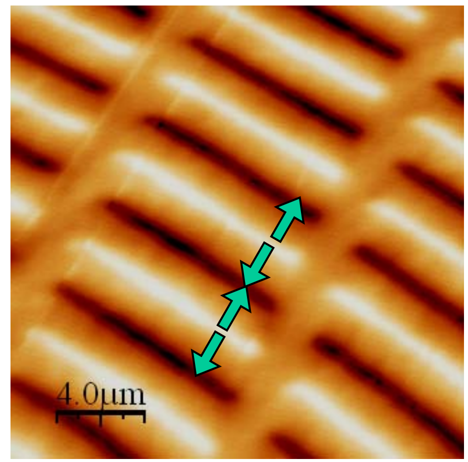
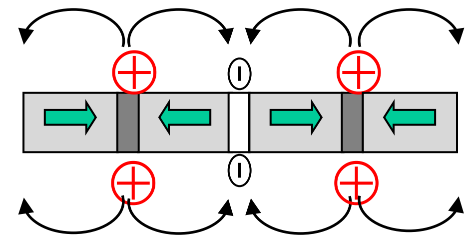
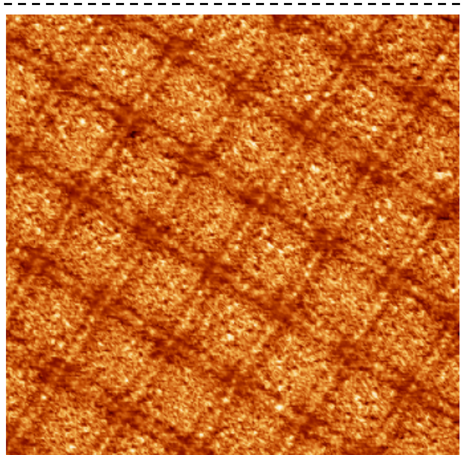
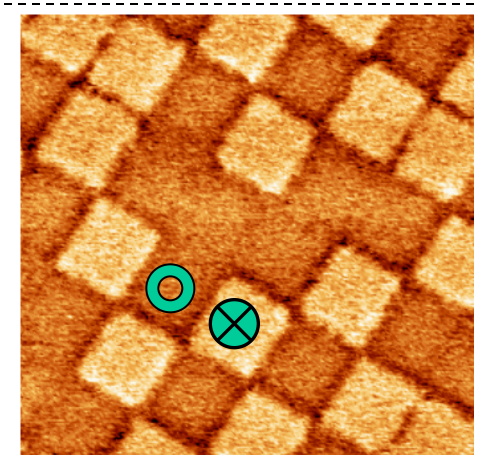
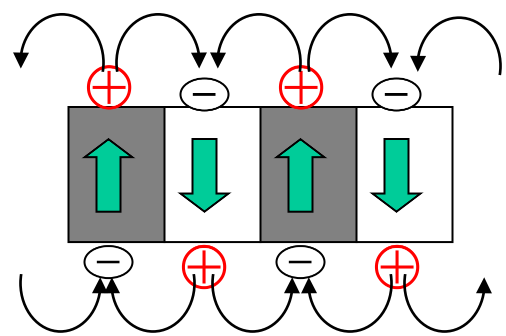
$d\omega < 0 \rightarrow$ atracción

Magnetic Force Microscopy (MFM)

$$\boxed{d\omega = -\frac{\omega_0}{2k}\frac{\partial F_z^{ext}}{\partial z}}$$

Dado que $F_z = \mu_0\, m_{punta} \dfrac{dH_{muestra}}{dz}$

el contraste es debido a los polos

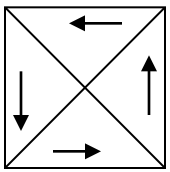
Anisotropía Mag.	AFM: topografía	MFM: magnetismo	Esquema (sección)
En el plano **Ej.: disco duro (CoPtCr)**			 **Vemos fronteras: PAREDES**
Perpendicular **Ej.: Co/Pt estructurado por FIB**			 **Vemos DOMINIOS**

Magnetic Force Microscopy (MFM)

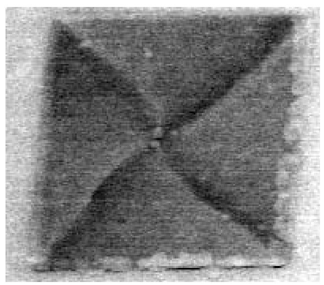
Perturbaciones debidas a la punta del microscopio

Curvatura aparente de las paredes de dominio

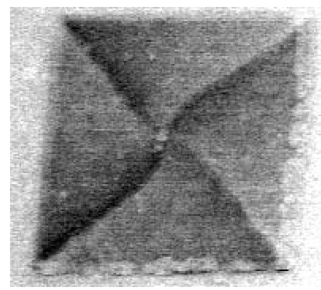
NiFe L = 2 μm
espesor: 16 nm

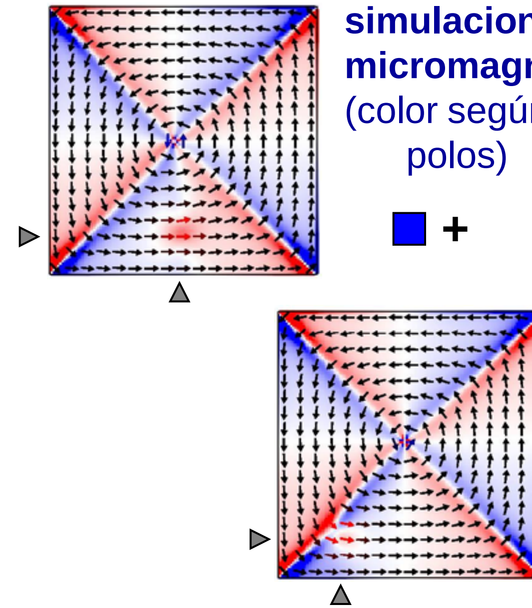


punta ⊙



punta ⊗



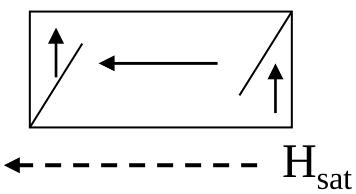


simulaciones micromagnéticas
(color según los polos)

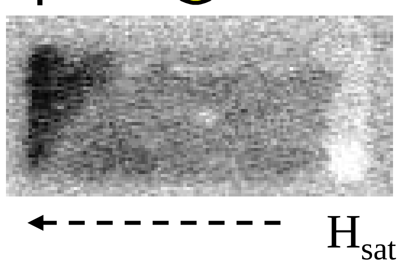
+ -

Asimetría aparente en los dominios de cierre

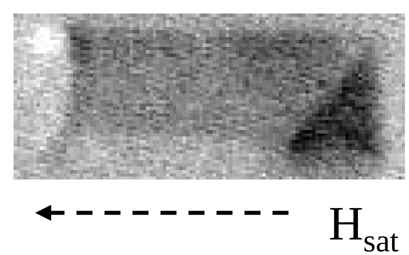
2 μm x 0.7 μm
espesor: 16 nm

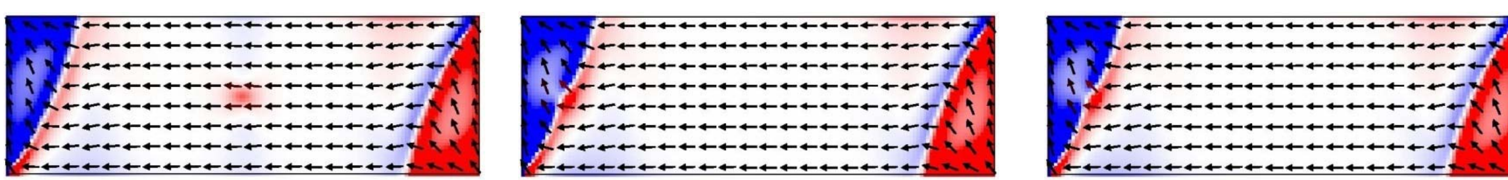


punta: ⊙



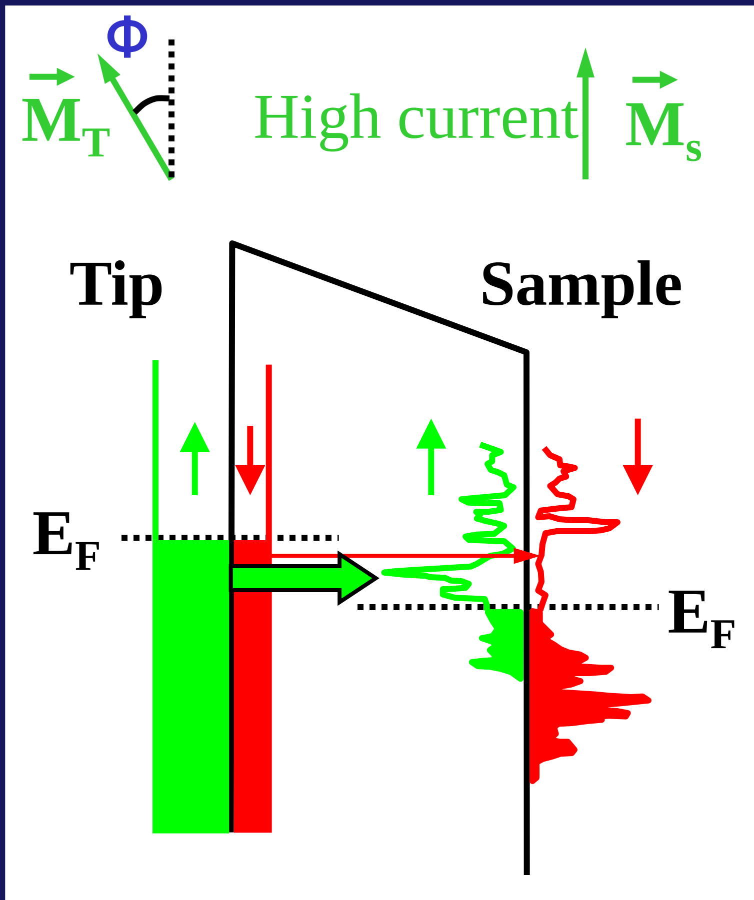
punta: ⊗

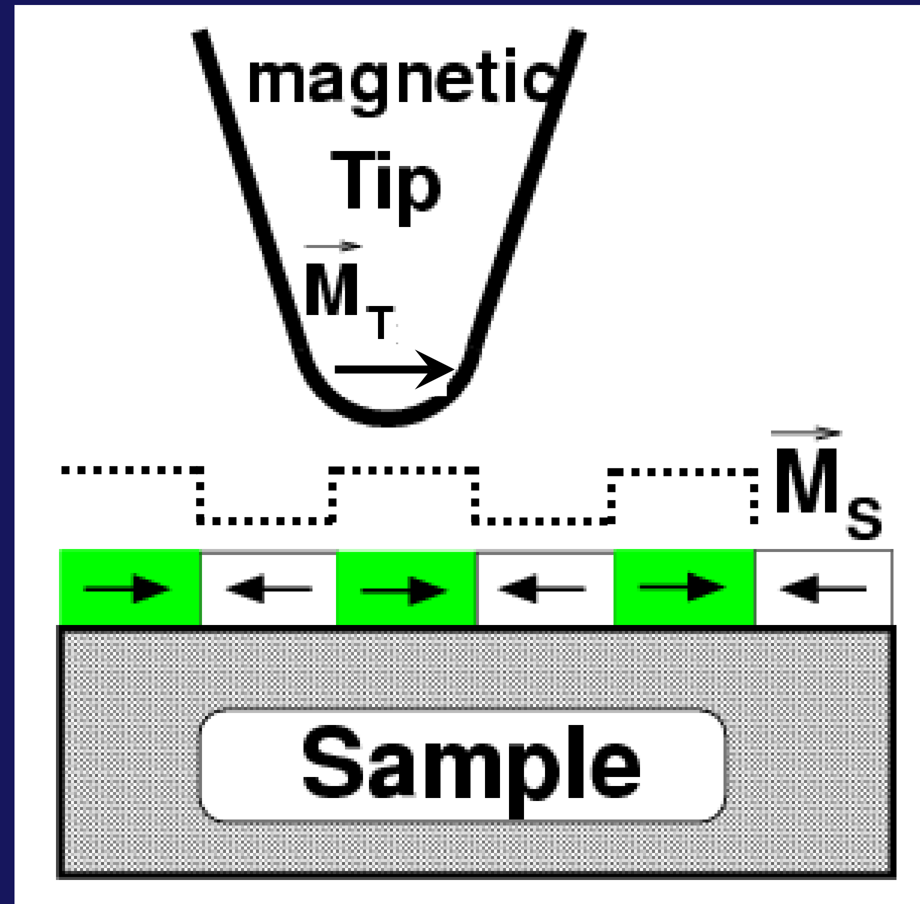




Spin-polarized STM

(cortesía de Amadeo L. Vázquez de Parga, UAM)





If tip and sample are magnetic, is necessary to take into account the spin-polarized electronic structure of both

The intensity of the tunneling current depends on the relative orientation between the magnetization axes of tip and sample

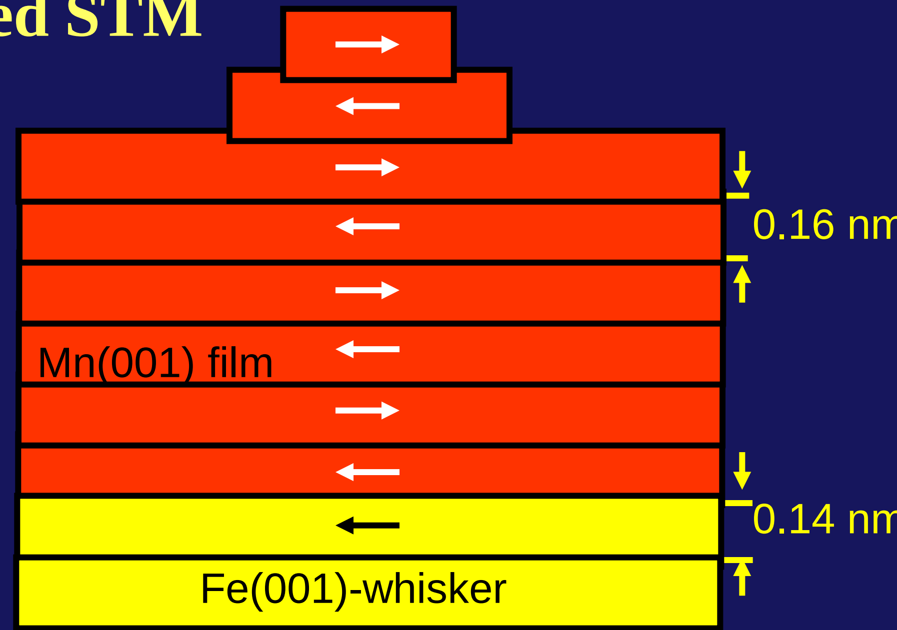
M. Bode, Rep. Prog. Phys. **66**, 523 (2003)

Spin-polarized STM

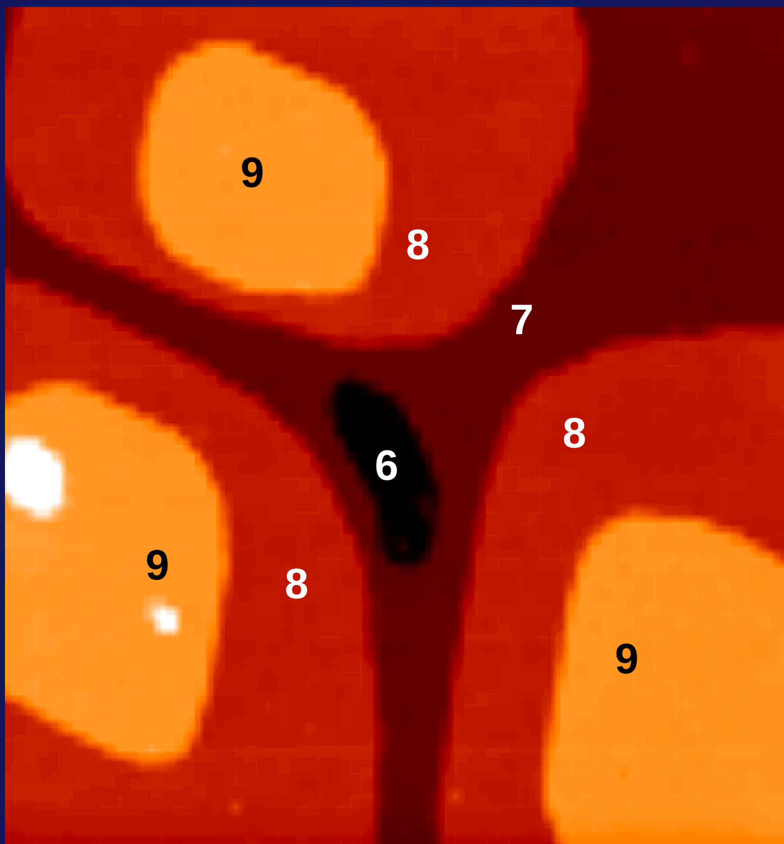
Sample: Mn/Fe(001)

Mn grown at 370 K (<4x10^{-10}mbar)

Body-centered tetragonal (bct)



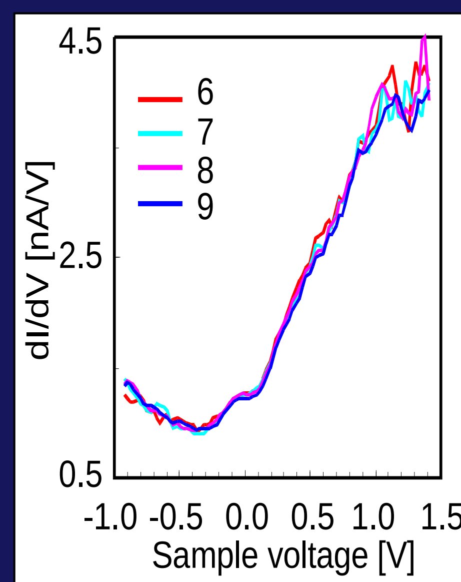
STM image after depositing 7 ML



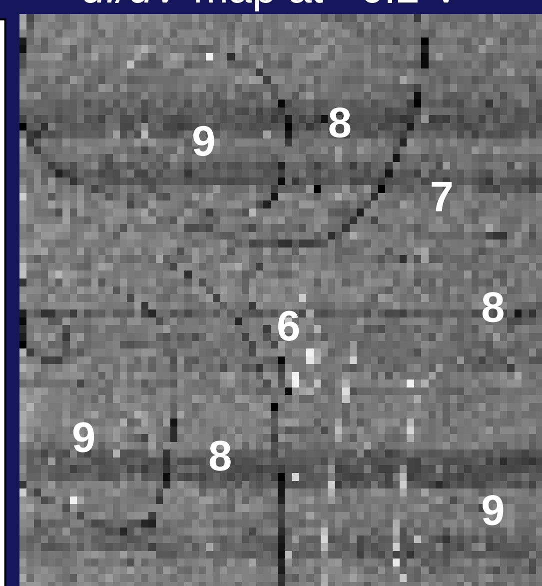
140 x 150 nm^2
V_s= - 0.5 V I=0.5 nA

STS measured with clean W tip

dI/dV curves



dI/dV map at +0.2 V

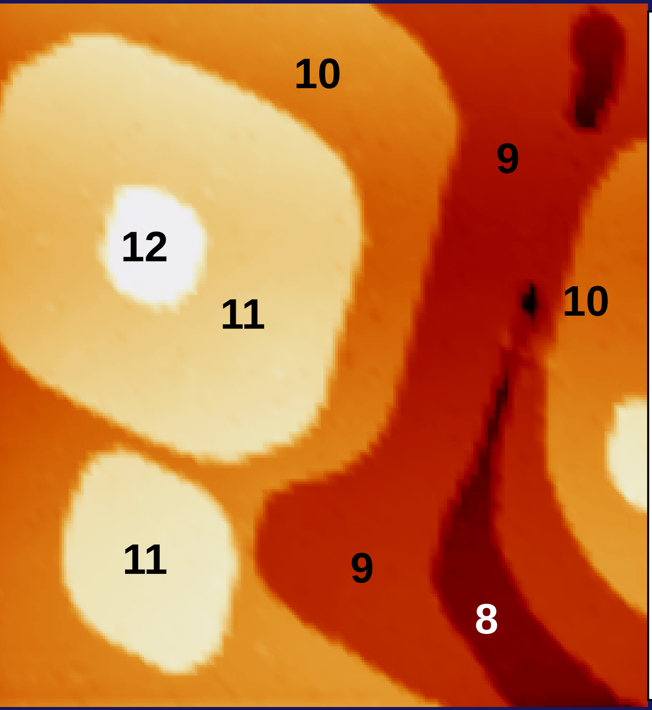


Spin-polarized STM

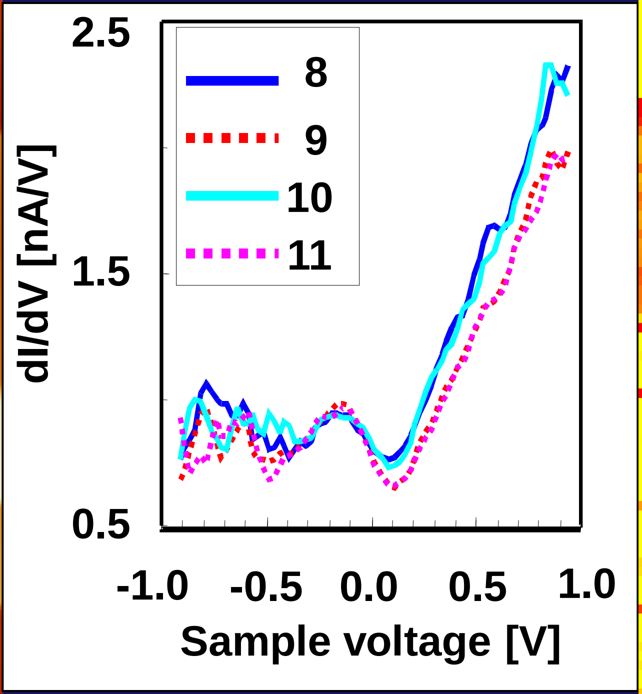
SP-STS on 9 ML Mn/Fe(001)

STS measured at room temperature with Fe-coated W tip

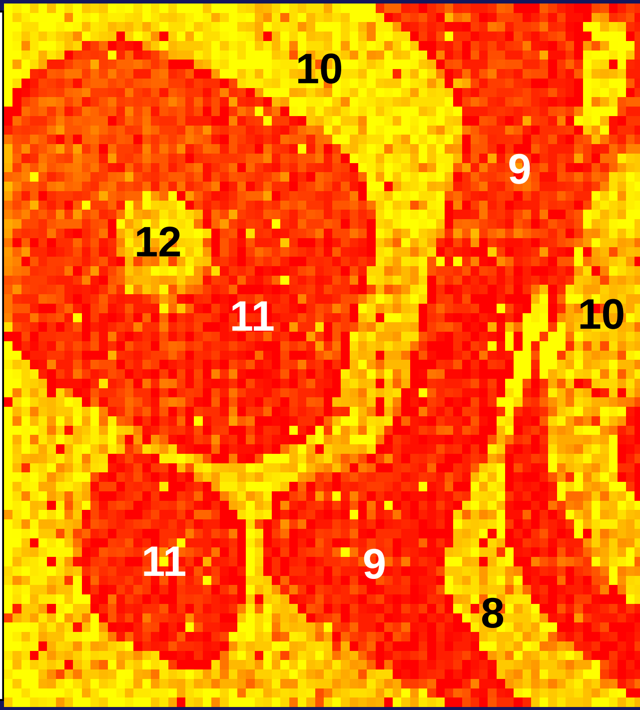
STM image



dI/dV curves



dI/dV map at +0.2 V



100 x 100 nm^2
V_s= - 0.5V, I=0.5nA

100 x 100 nm^2

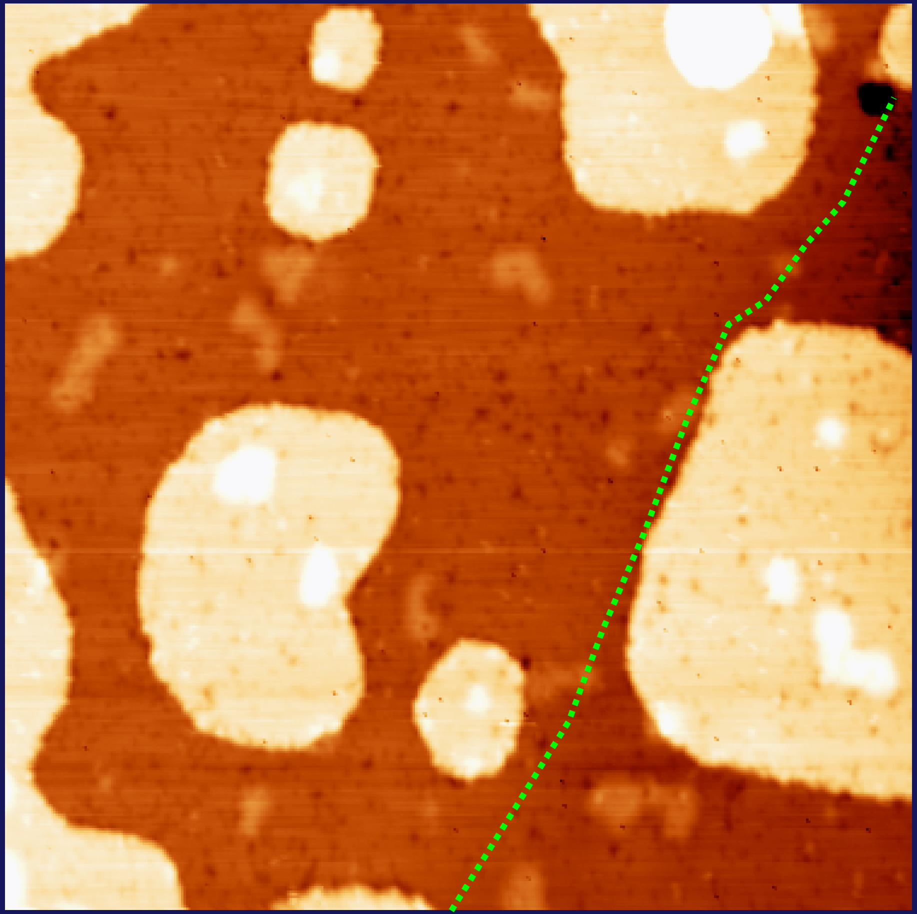
With the Fe-coated W tip alternating contrast with a clean W tip there is no contrast

Reversed contrast with different Fe-coated W tips due to different tip magnetization

Spin-polarized STM

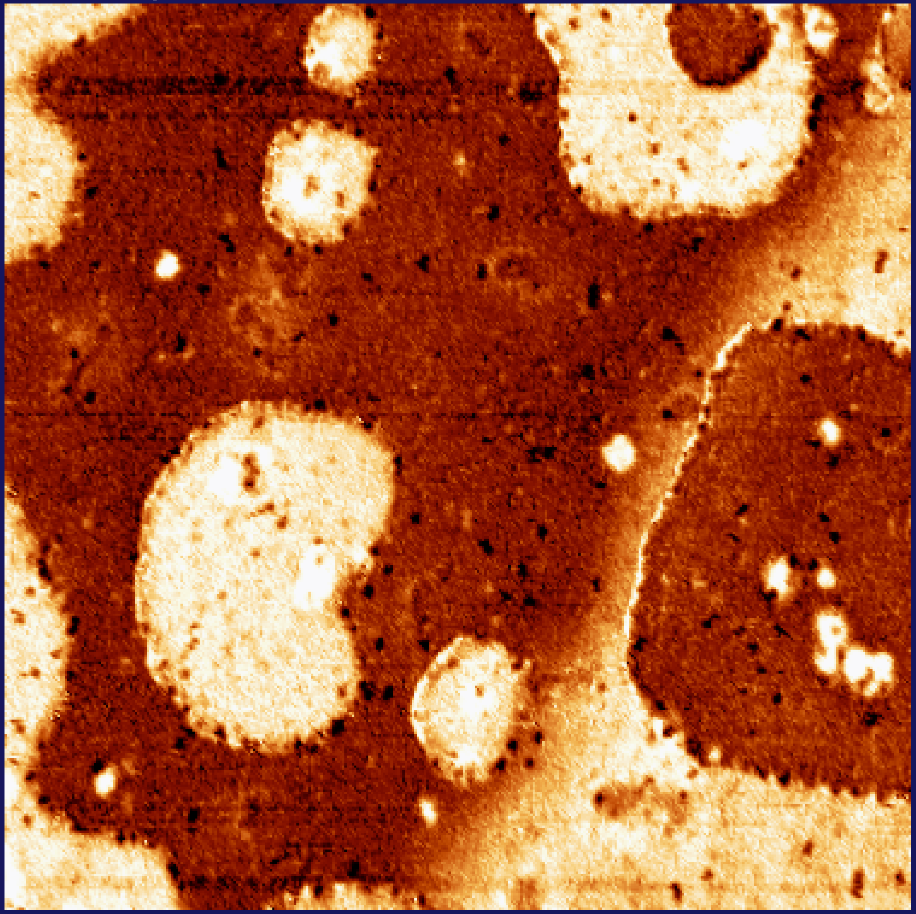
6.5 ML of Mn/Fe(001)

100 x 100 nm^2

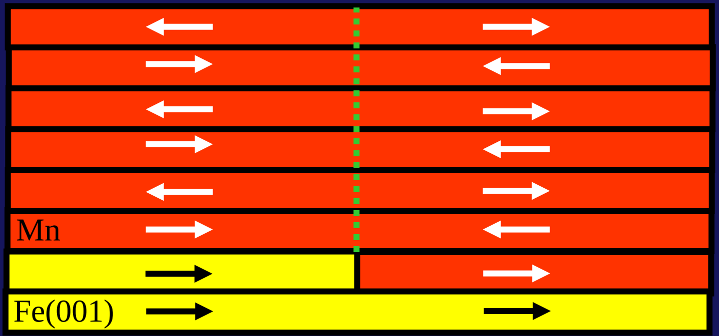


Topography

I map at V=0.20 V



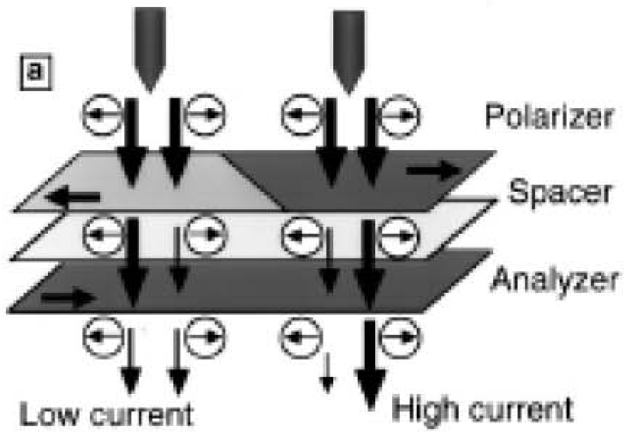
Measured at room temperature



Ballistic Electron Magnetic Microscopy (BEMM)

Basada en STM + Magneto-resistencia

W.H. Rippard, R.A. Buhrman
Appl. Phys. Lett. 75 1001 (1999)



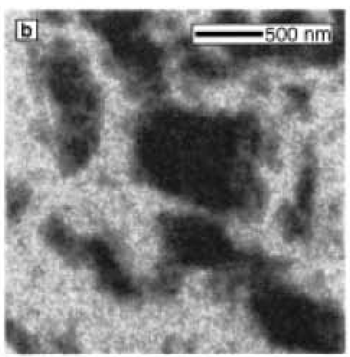
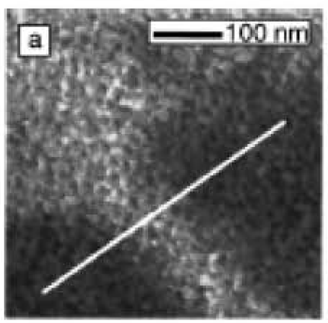
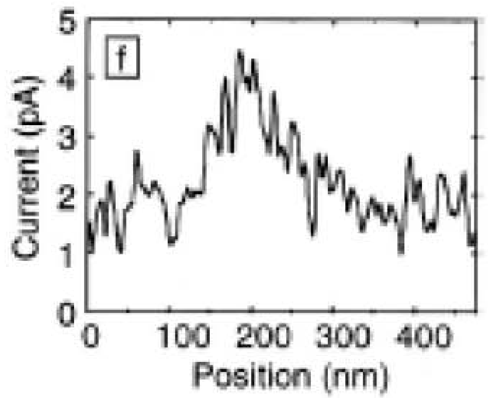


FIG. 1. (a) Schematic diagram of the "analyzer–polarizer" geometry showing how magnetic contrast is obtained in a ferromagnetic–normal-metal–ferromagnetic system. (b) Large-area ($2.5\times2.5\ \mu m^2$) scan taken after the sample has been biased into the coercive state with an applied magnetic field and the field then removed. The collector current is represented in a linear gray-scale with a range from 1.0 pA (black) to 5.0 pA (white), the background has been subtracted to enhance visual contrast. $V_t=-1.5$ V and I_t $=2$ nA.





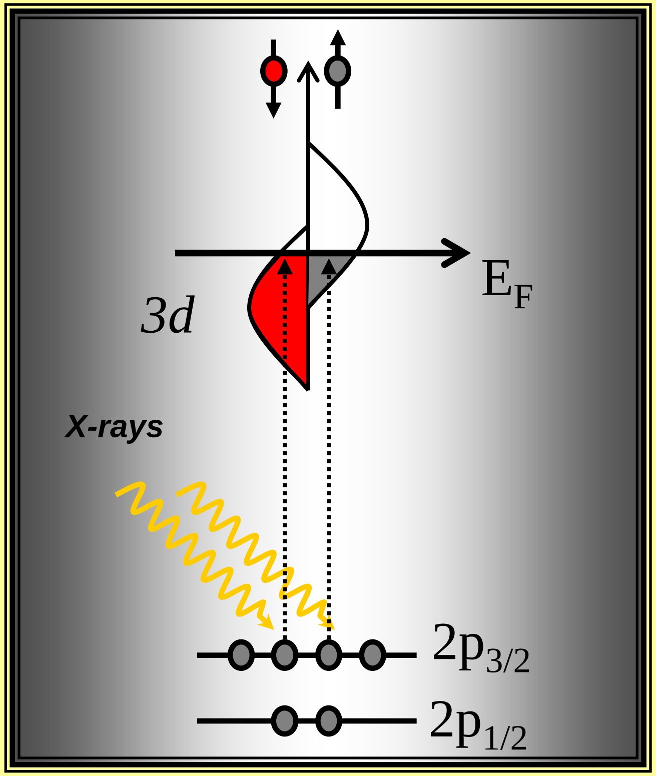
X-rays Photo Electron Emission Microscopy (X-PEEM)

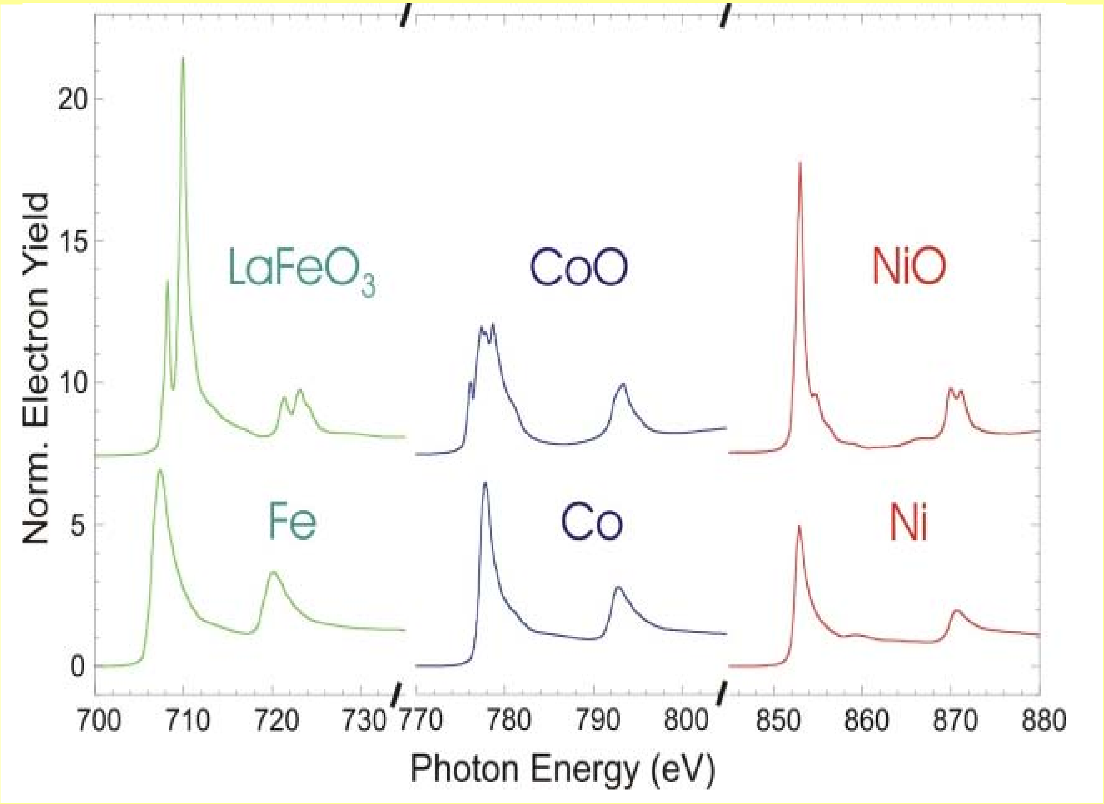
(cortesía de Julio Camarero, UAM)

X-ray Absorption Spectroscopy, XAS

- **XAS**: Convolution of the occupied density of states of the core levels and the unoccupied density of states

✓ ***element*** *and* ***chemical selectivity;***





Metallic and ionic character is easily identified at the absorption edges

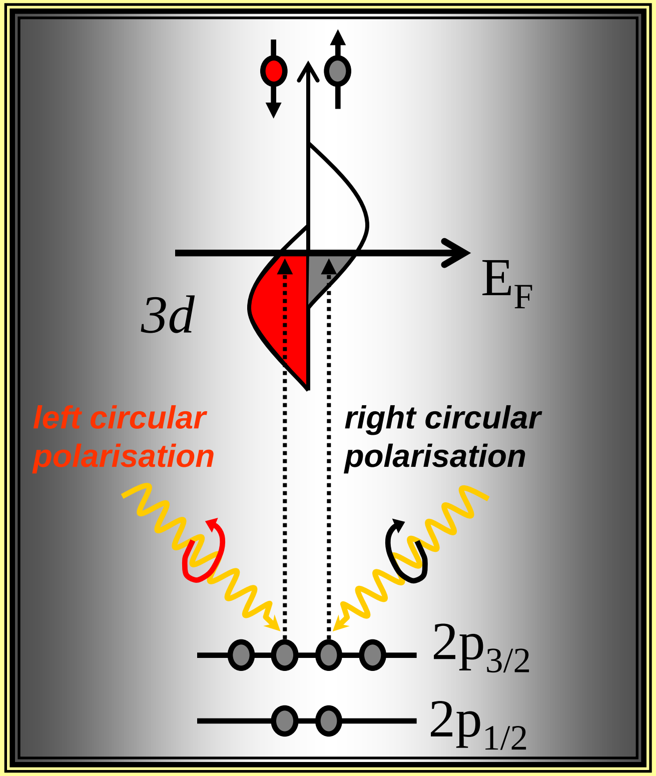
X-rays Photo Electron Emission Microscopy (X-PEEM)

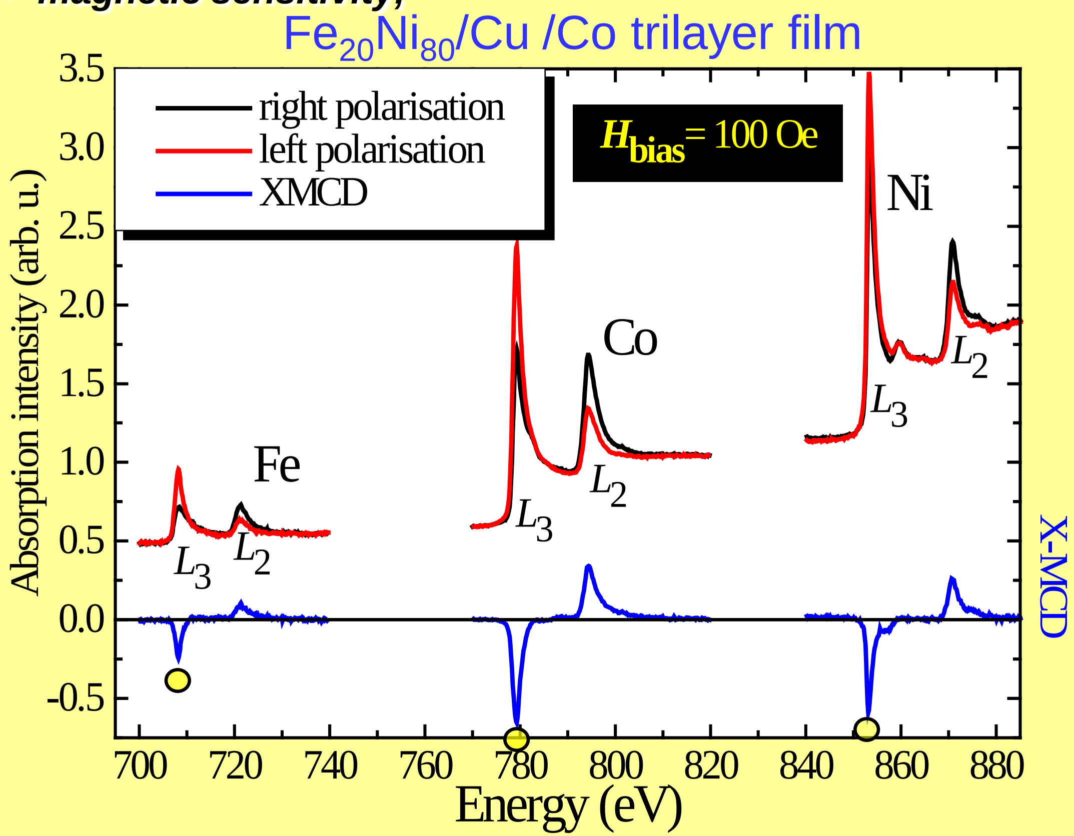
X-ray Magnetic **CircularDichroism XMCD**

- difference of absorption of x-ray photons of right and left polarisation [Schütz *et al* PRL **58, 737**(1987)],
- spin and orbital magnetization of the absorbing atom. [Thole *et al*. PRL **68**, 1943 (1992)],

✓ ***element and** chemical selectivity;*

✓ ***magnetic sensitivity;***

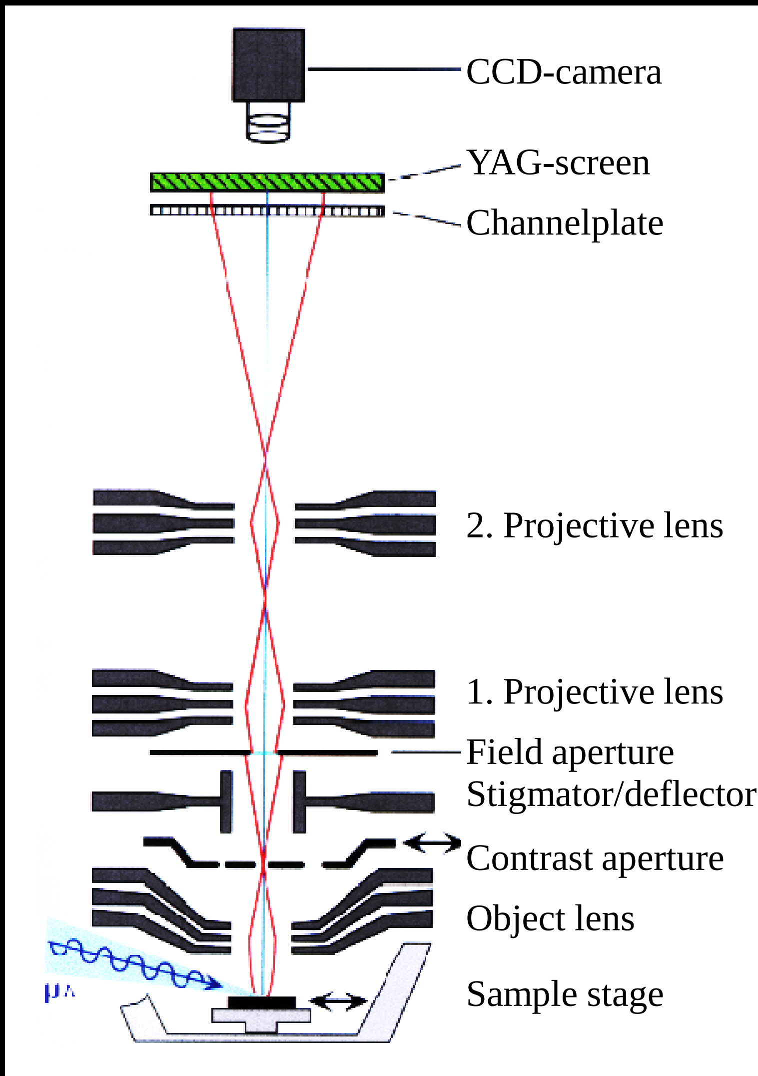




Element-selective hysteresis measurements at the maximum of the XMCD (L_3-edge)

Phys. Rev. Lett. **91**, 027201 (2003)

X-rays Photo Electron Emission Microscopy (X-PEEM)



- photoelectrons emitted from the sample are projected on a fluorescent screen by electron lenses.
- the intensity of the secondary electrons depends approximately linearly upon the photoabsorption intensity:

PEEM image ⬄ XAS intensity distribution

Since electrons are used for imaging the resolution is ***no longer-diffraction limited*** by the wavelenght of the incoming photons

When used in XMCD microspectroscopy, PEEM is set to observe the secondary electrons emitted as a consequence of the absorption of soft X-rays.

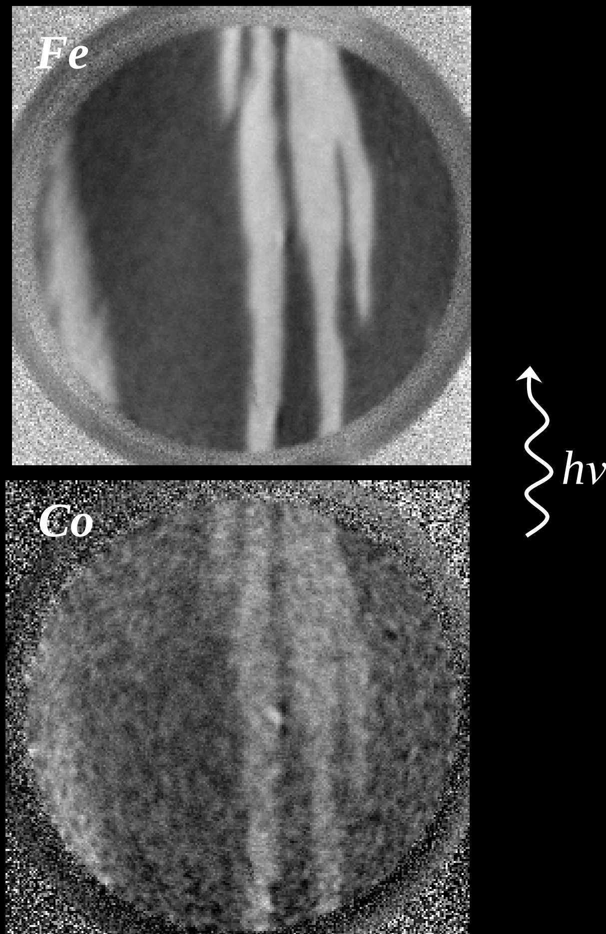
combining PEEM with XMCD, sub-μm resolution and element selectivity can be achieved

X-rays Photo Electron Emission Microscopy (X-PEEM)

Phys. Rev. B Rapid Comm. **69**, 180402 (2004)

*after a single **ms** pulse*

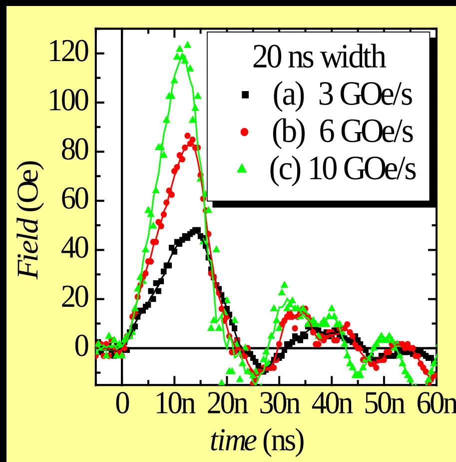
5nm FeNi/**8 nm Cu/**5nm Co/Si(111)

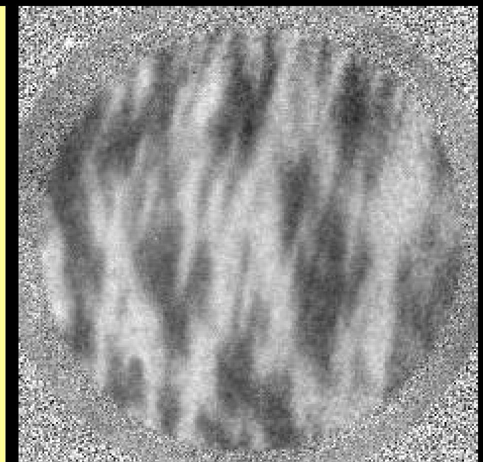


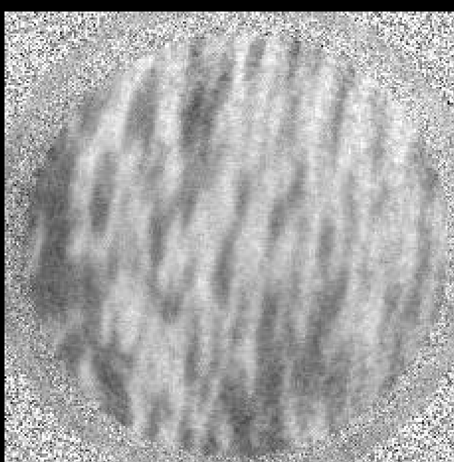
layer resolved magnetic properties

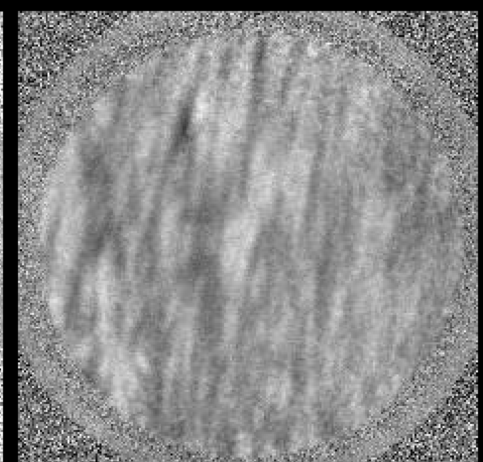
*after a single **ns** pulse with different amplitudes*

spin valve 5nm FeNi/10nm Cu/5nm Co





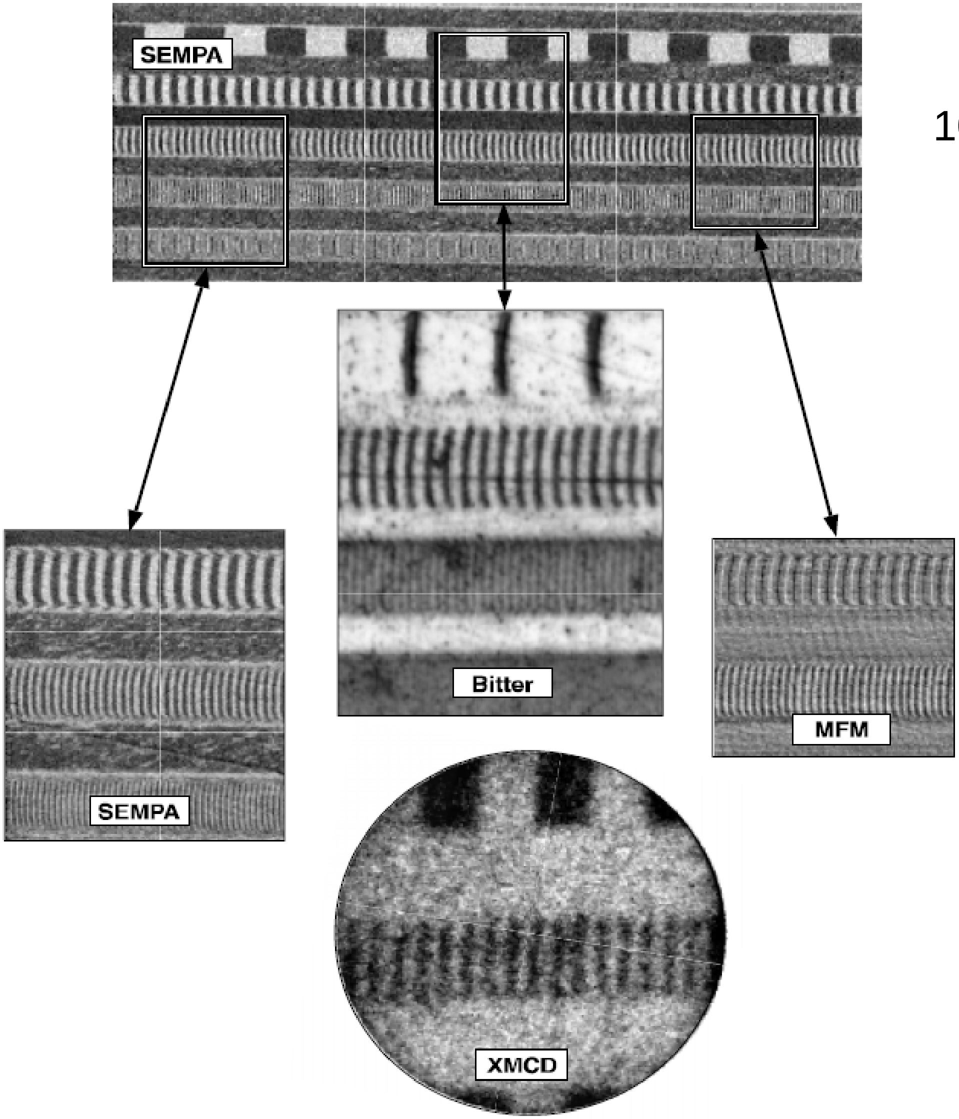




nucleation regime dominant at high sweep rates

Comparativa entre técnicas

10 to 0.2 microns

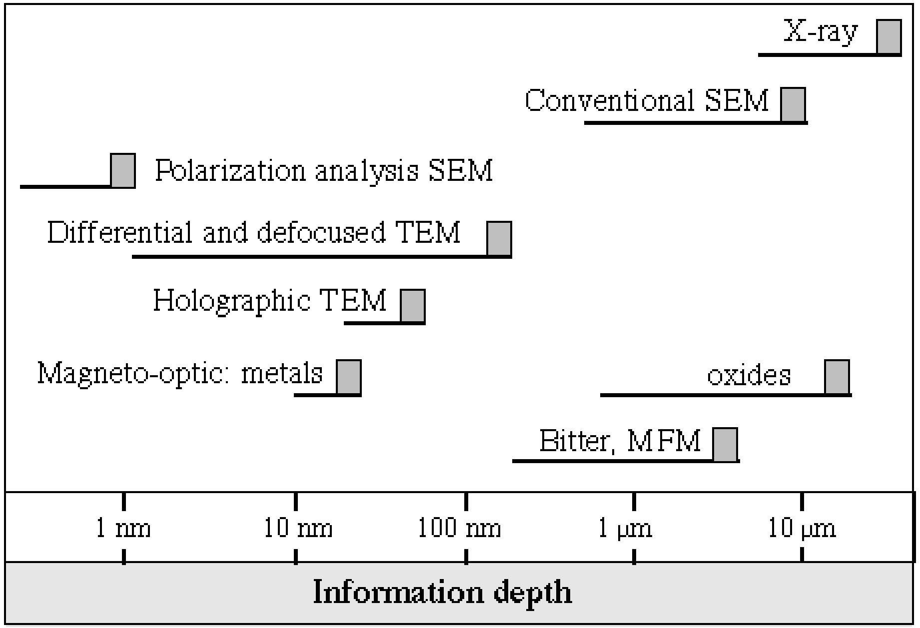


Comparativa entre técnicas

Technique	Signal	Sample preparation	Spatial resolution	Contrast	Materials	External field	Drawback
Magneto-Optical	Light polarization	Flat and Smooth surfaces	200nm	Walls and domains	K_{per} and $K_{in\text{-}plane}$	Available	Resolution
Bitter	Magnetic colloids distribution	None	100nm	Walls	High stray fields	Available (low speed)	Dirty Sample
SEMPA	Polarized S.E	HV cleaning	50nm	Domains	K_{per} and $K_{in\text{-}plane}$	Difficult	Cleanness
MFM	Charge density	None	20nm	Walls and domains	K_{per} and $K_{in\text{-}plane}$	Available	Tip-sample interaction
Lorentz	$F_{lorentz}$	UHV cleaning	~nm	Domains	$K_{in\text{-}plane}$	Difficult	Sample preparation

(cortesía de Agustina Asenjo, ICMM-CSIC)

Comparativa entre técnicas



From “Magnetic Domains”, Hubert & Schaeffer, Springer